NACA RM L54K18

RESEARCH MEMORANDUM

INVESTIGATION OF TWO SHORT ANNULAR DIFFUSER CONFIGURATIONS UTILIZING SUCTION AND INJECTION AS A MEANS OF BOUNDARY-LAYER CONTROL

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

January 25, 1955

[redacted]

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SUMMARY

The performances of two annular diffuser designs applicable to turbojet afterburner installations were investigated to determine the effectiveness of injection and suction boundary-layer controls. The outer shell was cylindrical in each case. The basic center-body design was an abrupt dump type which produced an equivalent conical diffuser angle of approximately 100°. The addition of a conical center-body fairing to the basic design produced a second configuration corresponding to an equivalent conical diffuser angle of 32°. Both designs had an area ratio of 1.9:1 and were tested with fully developed pipe flow at the inlet up to a Mach number of 0.45.

For the largest injection-slot opening investigated on the 100° diffuser, injection at a rate of 3.4 percent produced effective control over the velocity distribution, a 33-percent increase in the measured static-pressure rise, and a 50-percent reduction in the measured loss coefficient. Pumping power corrections reduced the 33-percent increase in static-pressure rise to about 21 percent and eliminated the reduction in loss coefficient. Suction control in the 100° diffuser was not efficient because of the extensive backflow region downstream from the dump. Suction control in the fairing configuration produced effective control over the velocity distribution, but the performance in terms of static-pressure rise and loss coefficient was not efficient because of the inadequate center-body design upstream from the auxiliary flow slot. The 100° diffuser with injection compared favorably with the performance of a 31° diffuser with an approximately elliptically shaped center body previously tested with vortex-generator controls.

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INTRODUCTION

The performance characteristics of subsonic-annular-diffuser designs applicable to turbojet afterburners are being studied in a research program initiated to develop short configurations approximately one outer diameter or less in length which provide stable flow, minimum total-pressure loss, and reasonably uniform diffuser-exit velocity distributions over at least 80 percent of the cross-sectional area. These goals are required in order to achieve efficient overall engine performance.

Comprehensive investigations of the effectiveness of vortex generators with annular diffusers varying in the ratio of length to outer diameter from zero to 1.0 (equivalent cone angles of 180° and 15°, respectively) are presented in references 1 to 5. The general configuration consisted of a cylindrical outer body and an inner body having a progressively decreasing diameter. The results of these investigations indicated that more favorable velocity distributions were obtained at the downstream station corresponding to a length-diameter ratio of 1.0 (afterburner inlet station) when the inner body length was 50 to 60 percent of the outer body diameter. Such configurations were almost as efficient as the annular diffuser of reference 1, which had an equivalent cone angle of 15°. Although vortex generators were capable of producing considerable improvement, the desired control over the velocity distributions at the afterburner inlet station was not obtained. Therefore, research into other methods of boundary-layer control was undertaken.

A preliminary investigation of an abrupt dump-type diffuser with an equivalent cone angle of 125° (ref. 6) indicated that both suction and injection controls were capable of producing improved diffuser flow. Both types of control greatly improved the static-pressure rise through the diffusing region, but the results indicated the need for further research in order to reduce the amount of auxiliary flow required for satisfactory diffuser performance and to reduce the pumping losses in the auxiliary flow.

The purpose of the investigation reported herein was to extend the preliminary work done by Henry and Wilbur (ref. 6). The diffuser center body was longer than that of reference 6 and provided a more gradual initial diffusion rate prior to its abrupt termination. The auxiliary flow slot was located adjacent to the main stream in order to provide a maximum of control over the diffusion. The slot alinement was designed so that the injection stream would tend to form a cone with the vertex on the diffuser center line at the station corresponding to a length-diameter ratio of about one-half. The slot was arranged in this manner in order to provide a maximum of control over the velocity distribution in the central region of the diffuser and in order to provide ample length for natural mixing at the downstream end. A second diffuser configuration, which was obtained by attaching an approximately conical fairing to the terminal of the center body, was tested in order to evaluate the effect of the abrupt dump on the performance.

The present investigation was conducted with fully developed pipe flow at the diffuser inlet. Performance was determined with no boundary-layer controls and with suction and injection. Most of the tests were conducted at an inlet Mach number of approximately 0.26, although the Mach number range was varied in some cases from approximately 0.18 to 0.45 with a resulting maximum Reynolds number (based on the inlet hydraulic diameter) of approximately 1.6×10^6.

SYMBOLS

D	diffuser outer diameter
d	hydraulic diameter, $\dfrac{4 \times \text{cross-sectional area of duct}}{\text{Perimeter of duct}}$
H	total pressure
ΔH	total-pressure loss
l	longitudinal distance measured from start of geometric diffusing region
M	Mach number
m	mass flow
n	exponent in expression for boundary-layer velocity distribution, $\dfrac{u}{U} = \left(\dfrac{y}{\delta}\right)^n$
p	static pressure
Δp	static-pressure rise
P	auxiliary air pumping-power coefficient, $\dfrac{R_I}{100}\left(\dfrac{H_I - \bar{p}_1}{\bar{q}_{c_1}}\right)$ or $\dfrac{R_S}{100}\left(\dfrac{\bar{H}_1 - H_S}{\bar{q}_{c_1}}\right)$

q_c impact pressure, $H - p$

R ratio of auxiliary air volume flow to main stream volume flow at inlet station, percent

u local velocity

U maximum velocity occurring in radial velocity distribution

y perpendicular distance from outer wall

δ boundary-layer thickness

δ^* boundary-layer displacement thickness, $\int_0^\delta \left(1 - \frac{u}{U}\right)dy$

θ boundary-layer momentum thickness, $\int_0^\delta \frac{u}{U}\left(1 - \frac{u}{U}\right)dy$

δ^*/θ boundary-layer shape parameter

η diffuser effectiveness, $\left[\frac{\frac{\Delta p}{\bar{q}_{c_1}}}{\left(\frac{\Delta p}{\bar{q}_{c_1}}\right)_{Ideal} + P}\right]$

Subscripts:

1 diffuser inlet station

1a reference static-pressure station

2, 3 downstream diffuser stations

x variable downstream diffuser station

S suction

I injection

A bar over a symbol indicates a mass-weighted average quantity.

APPARATUS AND PROCEDURE

Test Equipment

The general test apparatus is shown in figure 1(a). Air was induced through the diffuser by an exhauster fan connected to the downstream end. The inlet boundary layer was developed in approximately 27 feet of upstream annular ducting. The center body of the annular approach duct was used as an auxiliary air duct and was connected to a blower or exhauster according to whether injection- or suction-flow control tests were in progress. The auxiliary air duct was fitted with a flow-measuring orifice designed and installed according to A.S.M.E. standards (ref. 7).

The diffuser inner body was cylindrical with the downstream end rounded to a $3\frac{5}{8}$-inch radius as shown in figure 1(b). For convenience, the curved portion of the inner body will herein be referred to as the "cowl," and the circular plate which serves as the inner wall for the auxiliary air gap will be referred to as the "plug." The plug was translated axially to vary the size of the auxiliary air-flow gap. A fairing was attached to the downstream face of the plug for some of the configurations tested (see figure 1(b)). An angular connotation will be used herein to define annular diffusers. This connotation is defined as the total included angle of an equivalent straight-walled conical diffuser possessing the same inlet and exit areas and diffuser length. With this system, the basic diffuser of the subject report has an equivalent cone angle of approximately 100°, and the basic innerbody and fairing has an equivalent cone angle of 32°.

Instrumentation

Stream total and static pressures were measured by four equally spaced, remote-controlled survey rakes at stations 1, 2, and 3. Flow surveys were made at only one station at a time so that there were no instruments in the stream ahead of the measuring station. Stagnation-temperature and reference-pressure measurements were taken at a point in the approach annulus several hydraulic diameters upstream from the diffuser inlet (station 1), and measurements of the stagnation pressure and temperature were taken in the auxiliary air duct about 1 innerbody diameter upstream from the plug.

One row of static-pressure orifices was installed in a longitudinal plane in the outer wall from a point upstream of the diffuser inlet station to a point about 1 diameter downstream of station 3. At stations 1(a), 1, and 3, four equispaced static orifices were located circumferentially in the outer wall. In order to observe the flow, rows of small wool tufts were installed along the outer and inner walls between stations 1 and 3 and were found to have no effect on diffuser performance. All pressure measurements were made with multitube manometers containing a fluid whose specific gravity was 1.75. The manometer scales were read to the nearest millimeter.

Tests

The performance of the diffuser was measured over a Mach number range from $\overline{M_1} = 0.18$ to 0.40 with the plug positioned to give a zero gap. Total- and static-pressure surveys were made at stations 1, 2, and 3 for the diffuser with and without the fairing attached to the plug. Most of the runs with boundary-layer control were made at an $\overline{M_1} \approx 0.26$ with gap settings of 0.031, 0.062, and 0.121 inch. Surveys were made at two downstream stations (stations 2 and 3) in order to indicate the development of flow downstream from the diffuser as it proceeded through the tailpipe. The surveys at station 2 gave an indication of the velocity distribution at that point, although the accuracy was low because of the radial velocity components, flow asymmetries, and high turbulence level. The surveys at station 3 gave more accurate velocity distributions and loss coefficients than those at station 2; therefore, the relative performance of the various configurations is presented for this station, which was 1.09 outer body diameters from the start of the geometric expansion.

Basis of Comparison

The description of the flow at station 1 is presented in terms of the velocity ratio u/U in order to indicate the quality and character of the inlet boundary-layer distribution. The flow development in the diffuser is presented in terms of the outer wall longitudinal distribution of static-pressure coefficient $\frac{\Delta p_{x-1a}}{\bar{q}_{c_1}}$. The coefficient is referenced to the static pressure at station 1a, which was sufficiently upstream to be insensitive to flow or configuration changes between stations 1 and 3. The radial distribution of relative velocity $u/\bar{u}_1$ describes the flow at stations 2 and 3 and, in addition, indicates the local reduction in velocity due to diffusion. The overall diffuser performance is presented in terms of the mean coefficients $\frac{\Delta p_{3-1a}}{\bar{q}_{c_1}}$ and $\left(\frac{\overline{\Delta H}_{1-3}}{\bar{q}_{c_1}}\right)_{\text{Measured}}$

Previous investigations have reported that in regions of turbulent flow, the pressure measurements as recorded by a pitot-static tube indicate values that are higher than is consistent with flow continuity. (See refs. 5 and 8.) This error can be evaluated in terms of mass flow if the inlet conditions are assumed to be correct. The measured mass flow at a downstream station, as obtained from an integration of the survey profiles, is greater than the corresponding measured mass flow at the inlet, whereas for continuity the flow must be constant through a a closed-flow system. The ratio of this mass-flow discrepancy to the inlet mass flow

$$\frac{\Delta m}{m_{Act}} = \frac{m_3 - (m_1 \pm m_{I\ or\ S})}{m_1 \pm m_{I\ or\ S}}$$

has been calculated for station 3 and indicates qualitatively the mean turbulence level at this station. No accurate method for correcting the measured loss coefficient is known to exist because turbulence distributions have not been determined and because the phenomenon in general has not been evaluated experimentally. If it is imperative that a corrected value of loss coefficient be estimated for purposes of engineering approximation, the use of the following equation is suggested:

$$\left(\frac{\overline{\Delta H}_{1-3}}{\bar{q}_{c_1}}\right)_{Corrected} = \left(\frac{\overline{\Delta H}_{1-3}}{\bar{q}_{c_1}}\right)_{Measured} + \frac{\bar{q}_{c_3}}{\bar{q}_{c_1}}\left[1 - \left(\frac{1}{\frac{\Delta m}{m_{Act}} + 1}\right)^2\right]$$

The above equation assumes that the measured impact pressure at station 3 should be reduced by the square of the ratio of inlet mass flow to the mass flow measured at station 3. The accuracy of the suggested equation is unknown.

For the purpose of evaluating the diffuser performance, the pumping power required for suction or injection control, must be determined. The pumping power coefficient is defined in figure 2. In order to evaluate the coefficient, it was necessary to assume a hypothetical source for the injection air and a hypothetical exit for the suction air. In both cases, the diffuser inlet was assumed as the reference station; thus, the auxiliary air system was confined to the diffuser proper and any variables which would be impossible to assess in applying the results were eliminated. It was assumed that the auxiliary air-flow pump operated at an efficiency of 100 percent. In the case of injection, it was assumed that a pump would have to supply a pressure rise equal to the difference between the inlet static pressure and the measured total pressure in the chamber upstream from the injection gap. For suction, it was assumed that the pump would supply a pressure rise equal to the difference between the inlet mean total pressure and the chamber total pressure.

The total-pressure loss of the diffuser, including the pumping-power consideration, is then evaluated as $\left(\frac{\overline{\Delta H}_{1-3}}{\bar{q}_{c_1}}\right)_{\text{Measured}} + P$. The diffuser effectiveness η is evaluated as $\dfrac{\dfrac{\Delta p_{3-1}}{\bar{q}_{c_1}}}{\left(\dfrac{\Delta p_{3-1}}{\bar{q}_{c_1}}\right)_{\text{Ideal}} + P}$, where $\left(\frac{\Delta p_{3-1}}{\bar{q}_{c_1}}\right)_{\text{Ideal}}$ is the theoretical, one-dimensional, isentropic static-pressure coefficient corresponding to the mean inlet static and total pressures and the diffuser area ratio.

RESULTS AND DISCUSSION

Inlet Measurements

In order to define the inlet-flow conditions, total- and static-pressure surveys were made at station 1 for four equally spaced circumferential positions. Ultimately, the weighted mean values of these measurements were used in determining the overall performance coefficients. Velocity profiles determined by using the survey data are presented in figure 3 in terms of the ratio of local velocity to the maximum velocity as a function of radial position in the annulus. Inasmuch as no significant circumferential variations were measured, the average of the four sets of data is presented. Figure 3 indicates that only small differences existed between the data for the inner and outer wall with respect to velocity profiles and the significant boundary-layer parameters. The boundary layer filled the entire annulus, similar to fully developed pipe flow, and the use of boundary-layer controls did not alter the inlet conditions for the range of variables tested. The inlet boundary layer of the investigation reported herein is essentially the same as that of references 2 to 6.

Flow Observations

Observations of small woolen tufts installed along the diffuser walls indicated that two definite and distinct flow patterns occurred during the investigation. The more stable flow pattern was established when the flow separated from the cowl a short distance upstream from the point at which the auxiliary flow was introduced to the diffuser. The other flow pattern was established when the flow remained attached to the cowl until its abrupt termination at the point where auxiliary flow was encountered. The attached flow was found to exist only for injection through gap settings of 0.062 and 0.121 inch without the fairing installed. At a gap setting of 0.062 inch, it was possible to obtain both flow patterns. The attached-flow case was normally obtained when the flow was initiated. After operating a period of time, the flow occasionally changed abruptly to the separated state. When separation became established, it was generally necessary to stop all air flow through the diffuser and then restart the blowers before attached flow could be reestablished. It was noted during the tests that attempts to inject the higher quantities of auxiliary flow were a frequent cause of the precipitation of separated flow. The tuft observations regarding the two states of flow were substantiated by downstream pressure surveys. When the flow was attached, moderate turbulence, as evidenced by the tuft fluctuations, was present on the outer wall downstream of the inner body, whereas for separated flow the tufts indicated violent turbulence.

As discussed previously, additional information may be obtained with respect to the relative turbulence of the flow under various conditions by comparing the mass-flow measurements at a downstream station with the measurements at the inlet station. Such a comparison is presented in figure 4 as a function of the percentage auxiliary flow. The data indicate that suction control produced higher mass-flow errors, and, therefore, higher turbulence levels, than injection. The higher values with suction are probably attributable in part to the inability of suction control to prevent flow separation from the cowl. The errors obtained with this diffuser are typical in magnitude of those obtained in the investigations of references 5 and 8. The data for station 2 are not presented because of the data scatter and inaccuracies; however, the trends observed are the same as those observed at station 3 but of greater magnitude.

Static-Pressure Distributions

Longitudinal static-pressure distributions.- A convenient index to the flow development for a given diffuser is the longitudinal static-pressure distribution, since the change in static pressure per unit length is indicative of the change of the mean impact pressure. Plots of the static-pressure-rise coefficient as determined from the outer-wall static-pressure orifices are given in figures 5 to 8 as a function of diffuser length for control and no control. The values given are slightly higher than mean values in the region immediately downstream from the center body because of radial pressure gradients such as those described in reference 4. In addition, the data have not been corrected for injection and suction pumping powers.

The data of the subject diffusers are compared with those of the 125° diffuser of reference 6 and the 31° diffuser of reference 5 in figure 5 for the cases corresponding to no-flow controls. An increase in the radius at the break from the $1\frac{1}{2}$ inches of the 125° diffuser to the $3\frac{5}{8}$ inches of the 100° diffuser improved the static-pressure-rise coefficient $\frac{\Delta p}{\bar{q}_{c_1}}$ approximately 100 percent at station 2 and 20 percent at station 3 in spite of separation from some position on the cowl. The addition of the fairing to form a 32° diffuser produced no significant improvement, probably because the flow was separated from the cowling upstream from the fairing. The 31° diffuser, similar in length but of different geometry from the cowl and fairing, produced the best performance. This result is probably due to the lower initial rate of expansion produced by the 12.55-inch radius joining the ellipsoid of the 31° diffuser to the cylindrical center body. The larger radius undoubtedly delayed separation to a larger area ratio. From the performance of these diffusers with no control and from flow observations, it is to be concluded that the cowl should be designed with a more gradual rate of area expansion (larger radius); thus, flow separation upstream from the auxiliary flow openings is prevented.

The improvement achieved in the longitudinal static-pressure distributions for the 100° diffuser through the use of injection or suction for boundary-layer control is shown in figures 6(a) to 6(d). The maximum improvements were achieved with injection control in a region corresponding to approximately $l/D = 1/2$, (station 2). This location corresponds to the point on the center line where the vertex of the cone of injection air occurs. Injection of auxiliary air was effective in increasing the static-pressure rise with either attached or separated flow on the cowl surface; however, with separated flow, more injection air was required to achieve a given performance. This condition is readily apparent in figure 6(b), where both separated- and attached-flow cases are presented for an injection flow rate of 2.15 percent.

The basic 100° diffuser, when utilizing suction as a flow control, was responsible for some improvement in the longitudinal static-pressure distribution, although it was largely ineffective when compared with injection. Figure 7 shows that the addition of the fairing to the basic design to produce a 32° diffuser increased the effectiveness of the suction control and indicated that suction could not control the backflow region in the 100° diffuser. Both configurations suffered from flow separation from the cowl with suction control. Figure 7 also shows that injection control with the fairing in place was very effective when the auxiliary flow (6.13 percent) was sufficient to eliminate separation.

A comparison of the longitudinal static-pressure rise for the 125° diffuser (ref. 6), the 100° diffuser, and the 100° diffuser with the fairing (equivalent to a 32° diffuser) is shown in figure 8 for injection quantities of $R \approx 5.0$ percent and suction quantities of $R \approx 3.7$ percent. These auxiliary-flow quantities were chosen because these conditions produced the most uniform velocity distributions at station 3 for one or more of the configurations, as will be discussed subsequently. The 31° diffuser with vortex generators (ref. 5) was also included in this figure in order to assess the relative merits of vortex generators and auxiliary flow.

With injection of 5.1 percent, the 100° diffuser produced higher static pressures throughout more of the diffusing region than any other configuration. The remaining injection configurations produced less $\frac{\Delta p}{\bar{q}_{c_1}}$ because of poorer basic design in the case of the 125° diffuser or because of separation on the cowl in the case of the 100° diffuser and fairing. The 100° and 125° diffusers produced higher rates of diffusion than the 31° diffuser with vortex generators in spite of the poorer basic design of the center bodies. Except for the case where the fairing was used to eliminate the extensive backflow regions, the configurations utilizing suction for flow control produced low values of $\frac{\Delta p}{\bar{q}_{c_1}}$.

<u>Static-pressure-rise coefficients, stations 2 and 3.</u>- The static-pressure-rise coefficients at station 3 are presented in figure 9 for the range of inlet Mach numbers. A small, unfavorable Mach number effect is evident for the no-control condition. For comparable auxiliary-flow rate, attached flow gives a wall static-pressure rise greatly exceeding the equivalent values obtainable with flow separation occurring on the inner body.

The effect of the auxiliary-flow quantity R on the static-pressure-rise coefficient at stations 2 and 3 is shown in figure 10 for a mean inlet Mach number of approximately 0.26. Station 2 is presented since it is in a region of maximum improvement due to control, whereas station 3 is at an l/D of 1.09, which is of most interest to afterburner design.

For the 100° diffuser at a given auxiliary-flow rate, attached flow produced a static-pressure rise about 30 percent higher than that for separated flow. For either condition, injection through the smaller gaps produced higher static-pressure rise for a given auxiliary flow rate. This effect is due at least in part to the higher total pressure of the auxiliary flow through the smaller gaps. Where sufficient data coverage exists, an optimum auxiliary flow rate is indicated for injection. With a larger radius cowl which with no control would provide attached flow up to the auxiliary-flow opening, it is expected that control would be more effective and would produce a higher static-pressure rise for a given auxiliary-flow rate.

The addition of the fairing was responsible for improved suction performance since the fairing forced the suction to act on the main-stream boundary layer instead of on the backflow region. Injection with the fairing failed to eliminate separation on the cowl for values of R less than about 6 percent; therefore, the performance for a given auxiliary flow rate was inferior to the 100° diffuser with attached flow.

Downstream Velocity Distributions

The velocity distributions at stations 2 and 3 for the no-control conditions are presented in figure 11. For purposes of comparison, the velocity distributions for no control for the 31° diffuser of reference 5 and the 125° diffuser of reference 6 are also included on this figure. At station 2, there is little difference between the distributions; all have a large region of separated flow that extends for approximately 4 inches from the diffuser center line. Natural mixing of the flow between stations 2 and 3 is responsible for some improvement in the distributions, especially with the longer center-body diffusers, but the profiles are still nonuniform.

Injection for flow control with the 100° diffuser (figs. 12(a) to 12(c)) produced improved velocity distributions in all cases as the auxiliary-flow rate increased; the attached-flow cases produced better distributions than the separated-flow cases for comparable auxiliary-flow rates, as evidenced by the data for gaps of 0.062 and 0.121 inch. For a gap of 0.121 inch, injection rates were obtained which produced almost uniform flow at station 3 except for the outer-wall boundary layer, which is unavoidable unless control is used on the outer wall. Presumably, with a better cowl design, the uniform distributions would have been obtained at lower rates of injection. The data indicate that, for a constant auxiliary-flow rate, smaller gaps produce better velocity distributions if attached flow can be maintained over the length of the cowl. This is a natural result of the higher total pressure of the injection air for the smaller gaps.

Suction, when used with the 100° diffuser (fig. 12(d)) had no effect on the cowl separation and less positive control over the backflow region. Therefore, suction had less effect over the velocity distributions than did injection.

The velocity distributions obtained at stations 2 and 3 with injection when the fairing was installed on the plug of the 100° diffuser are presented in figure 13(a). The addition of the fairing prevented the formation of the extensive backflow region and eliminated the mixing of the injection stream with this backflow; thus, the identity of the injection stream was preserved. This effect produced peak velocities in the central region at station 2 which were diffused by natural mixing between stations 2 and 3 and completely eliminated at station 3 for the lower rates of injection. Most of the advantage of conserving the injection total pressure by the elimination of the extensive backflow region was canceled by the separated flow on the cowl and resulted in little net effect on the velocity distribution due to the fairing installation. With a better cowl design, the deficiency in the velocity (or total pressure) between the injection stream and the main stream would have been reduced and the control would have been more effective.

At stations 2 and 3, suction with the fairing installed (fig. 13(b)) produced definitely superior velocity distributions to those obtained with suction and the 100° diffuser alone. The fairing, by eliminating the extensive backflow region, permitted the suction to act more as a boundary-layer control; whereas, without the fairing, the suction had to control the backflow region also. The profiles at station 3 indicate that suction of approximately 3.8 percent would have produced a nearly constant velocity in the central region.

For purposes of comparison, the velocity distributions obtained with injection of approximately 5.0 percent and suction of 3.7 percent are presented in figure 14 along with profiles for the 125° diffuser of reference 6 at corresponding auxiliary-flow rates and with the 31° diffuser of reference 5 when utilizing vortex generators. The values of the injection or suction auxiliary-flow rate correspond to nearly uniform velocity distributions for several of the configurations and were obtained from faired cross plots of the experimental velocity distributions. The 31° diffuser with vortex generators is included because the center-body length is comparable with the fairing configuration and also because this configuration produced one of the best distributions obtained with vortex generators.

It can be seen from figure 14 that with control the more uniform velocity distributions at station 3 are obtained with the 100° diffuser and fairing when suction is utilized, the 100° diffuser with injection, and the 100° diffuser and fairing with injection. Since the suction auxiliary-flow rate is only 3.8 percent, the 100° diffuser and fairing is definitely superior when suction is utilized for flow control. The 31° diffuser with vortex generators is inferior to the above three configurations. The 100° diffuser with suction and the 125° diffuser with injection produced the least uniform velocity profiles.

Both suction and injection are powerful flow controls; they are more effective than vortex generators for establishing uniform downstream velocity distributions. Locating the vertex of the injection cone approximately at station 2 provides ample length between station 2 and station 3 for the velocity distribution to become uniform through natural mixing and appears to be a sound design practice. This principle is in agreement with the results of reference 5, which indicate that center-body lengths of 50 to 60 percent of the overall diffuser length produced the best velocity distribution. It was not possible to determine the relative merits of suction and injection because the flow in some cases was separated from the cowl. For the same reason, the effectiveness of the fairing could not be fully evaluated.

Mean Performance Coefficients

Total-pressure-loss coefficient.- Measured total-pressure-loss coefficients (not corrected for pumping power or turbulence) between the inlet and stations 2 and 3 are presented in figure 15 as a function of the auxiliary-flow rate. With attached flow (injection through a gap of 0.121 inch) in the 100° diffuser, injection reduced the measured loss coefficient from a value of 0.188 for no control to a value of 0.094 at 3.4 percent auxiliary flow. Since figure 4 indicates a similar trend for the mass-flow discrepancy, the true rate of decrease in loss coefficient with injection would be higher than that shown in figure 15, according to the relation presented in the section, "Basis of Comparison." The losses at station 2 are somewhat less than those at station 3 due to the mixing and friction losses between the two stations. Suction data at both stations and the separated-flow injection cases at both stations correspond to high loss-coefficient values because of flow separation from the cowl. Injection data with separated flow have not been plotted for station 2 because of the scatter present. In general, the gap opening had no appreciable effect on the measured loss coefficient for a constant auxiliary-air-flow rate when suction was utilized.

The addition of the fairing was responsible for high loss coefficients with injection up to flow rates of approximately 5 percent that can be attributed to the flow separation from the cowl. Increased injection above 5 percent produced a rapid decrease in the measured loss coefficient that presumably indicates a progressive decrease in the extent of the separated-flow region. If the values for the total-pressure-loss coefficient were corrected for mass-flow discrepancies according to the method presented in a previous section, the same trends as obtained with the measured values would result, but the magnitudes would be considerably higher.

Coefficients corrected for pumping power.- In order to compare the data of the present report with other control systems and diffusers, it is necessary to evaluate the power cost of the auxiliary-flow system and to correct the performance measurements for this power. The pumping-power coefficients, calculated according to the methods of a previous section, are presented in figure 16 as a function of the percent of auxiliary flow. The power factor increases rapidly with increasing auxiliary flow and approximates a cubic function. Since the 100° diffuser had somewhat higher pressures in the region of the auxiliary-flow slot than were present after the fairing was installed, the power factor for injection is greater for the 100° diffuser, whereas the power factor for suction is greater for the 100° diffuser and fairing. For some of the higher injection runs utilizing a 0.031-inch gap, it is probable that the auxiliary flow was in a choked condition.

The diffuser effectiveness, including the pumping-power correction and based on the static-pressure-rise measurements to station 3, is presented in figure 17 as a function of percent auxiliary flow. An increase in the effectiveness of the 100° diffuser of 21 percent of that for the no-control condition was possible when attached flow was present on the cowl and injection quantities of 3.40 percent through a gap of 0.121 inch or 1.95 percent through a gap of 0.062 inch were utilized for flow control. This increase in the diffuser effectiveness corresponds with increases in the measured static-pressure-rise coefficient at station 3 of 33 percent and 21 percent, respectively. (See fig. 10.) Reducing the effectiveness values to corrected static pressure rise decreases this gain in measured performance by 40 and 5 percent for the 0.121-inch gap and 0.062-inch gap, respectively, as compared with the 85-percent reduction for the 125° diffuser of reference 6. The attached-flow cases (injection) indicate that the smaller auxiliary-air-flow gap, which corresponds to higher injection total pressure, was responsible for a decrease in the auxiliary-flow rate necessary to attain high performance. With a more satisfactory cowl design, stable and attached flow should be obtainable for all conditions with a gap of 0.062 inch; this design would result in better performance than with a 0.121-inch gap at the same auxiliary flow rate or the same performance at a lower auxiliary flow rate. With separated flow from the cowl, the diffuser efficiency, with or without the fairing, was much lower.

The total-pressure-loss coefficient corrected for pumping power (fig. 18) exhibited less loss with attached flow and injection control (100° diffuser) than for no control up to an auxiliary-flow rate of approximately 3.5 percent for the 0.121-inch gap. This trend would be accentuated by a correction for mass-flow error as previously discussed.

It should be noted that the auxiliary-flow rate that produced the lowest corrected loss coefficient did not correspond to that which produced the most uniform velocity distribution (see fig. 12(c)). No decrease in the corrected loss coefficient was possible with flow separation from the cowl by suction, gap variation, or the addition of the fairing.

A comparison of the performance coefficients for the diffusers of the present report with the 125° diffuser of reference 6 is presented in terms of the diffuser effectiveness and the corrected loss coefficient in figure 19 as a function of percent auxiliary flow. Performance points for the 31° diffuser with and without vortex generators have also been indicated on this figure. The effectiveness of the 100° diffuser is considerably higher than that of the 125° diffuser; this is due in part to the better no-control performance of the 100° diffuser that was brought about by increasing the radius of the innerbody cowl. The auxiliary-flow system was also more efficient and effective; this result presumably is due to the slot design being more efficient than holes and injection air adjacent to the main flow and towards the center line being more effective than that used with the 125° diffuser. The maximum effectiveness of the 100° diffuser falls between the no-control and control values of the 31° diffuser with vortex generators.

A comparison of the corrected loss coefficient indicates the decrease in loss that was obtained by slightly increasing the cowl radius and by using a more efficient auxiliary-flow system. Over the entire range of auxiliary flow tested, the 100° diffuser with an auxiliary-air-flow gap of 0.121 inch had appreciably lower values of the corrected loss coefficient than did the 125° diffuser of reference 6. These values for the 100° diffuser, although lower than those of the 125° diffuser, ranged from 15 percent to 50 percent higher than those for the 31° diffuser with vortex generators up to an auxiliary-flow rate of 3.7 percent. These comparative results would not be altered by a mass-flow-error correction.

CONCLUSIONS

A short annular diffuser with an equivalent conical diffuser angle of approximately 100° was investigated to determine the effect of suction and injection on the diffuser performance. A fairing was added to the basic diffuser to produce a second configuration with an equivalent conical angle of 32° and an approximately conical center body. The diffusers had a 21-inch-diameter straight outer wall, an area ratio of 1.9 to 1, and fully developed pipe flow at the inlet. Inlet Mach number was varied from 0.18 to 0.45 with a resulting maximum Reynolds number (based on inlet hydraulic diameter) of approximately 1.6×10^6. The ratio of the auxiliary air flow to the flow of the main stream was varied from 0 to approximately 6 percent. The following conclusions are presented:

1. The performance of both models tested was penalized with or without boundary-layer control by the inner-body design which corresponded to a rate of area expansion such as to produce flow separation upstream from the auxiliary flow opening with no control. Flow separation was eliminated only for the case of the 100° diffuser with injection through the larger gaps. Occasionally this attached-flow condition changed abruptly to the separated state. This flow change generally occurred with the intermediate gap and appeared to be irreversible.

2. For the attached-flow cases for the 100° diffuser, injection through the largest gap produced effective control over the velocity distribution. At an injection rate of 3.4 percent, a 33-percent increase in the measured static-pressure rise and a 50-percent decrease in the measured total-pressure loss were obtained. Pumping-power corrections reduced the static-pressure gain to 21 percent and eliminated the reduction in loss coefficient. The performance in terms of corrected pressure coefficients was inferior to that of a 31° diffuser previously tested with vortex generators; however, the velocity distributions were superior.

3. Suction control is not efficient when applied in an extensive backflow region such as exists immediately downstream of an abruptly terminated center body.

4. The addition of the fairing to the end of the center body of the 100° diffuser did not produce efficient performance corrected for pumping power because the auxiliary flow was unable to control flow separation on the cowl and high total-pressure losses resulted. Both injection and suction control with the 100° diffuser with fairing produced effective control over the velocity distribution. With suction control, the use of a conical center-body design, similar to that obtained with the fairing installation, offers substantial advantages in reducing the control requirements by eliminating the extensive backflow region.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 8, 1954.

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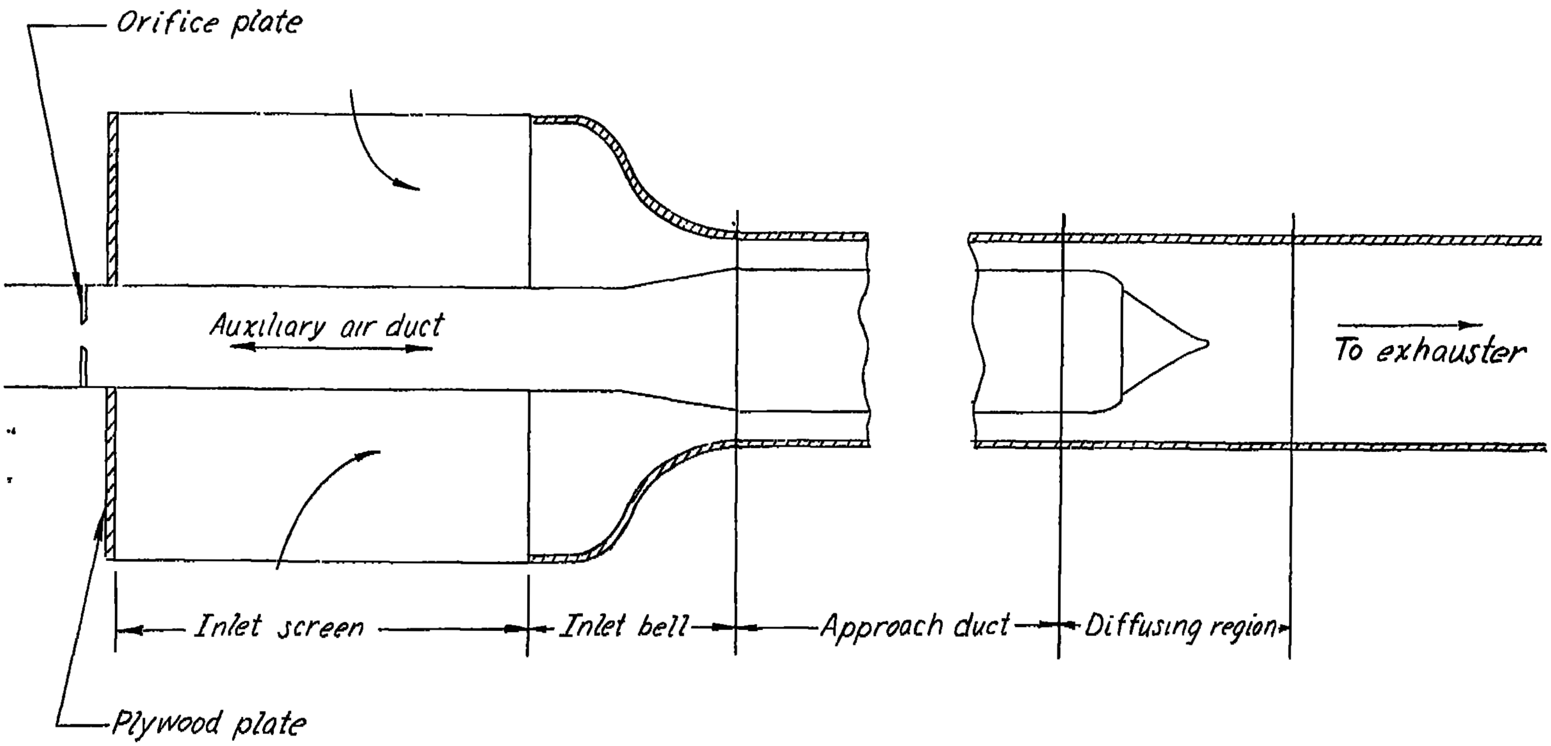
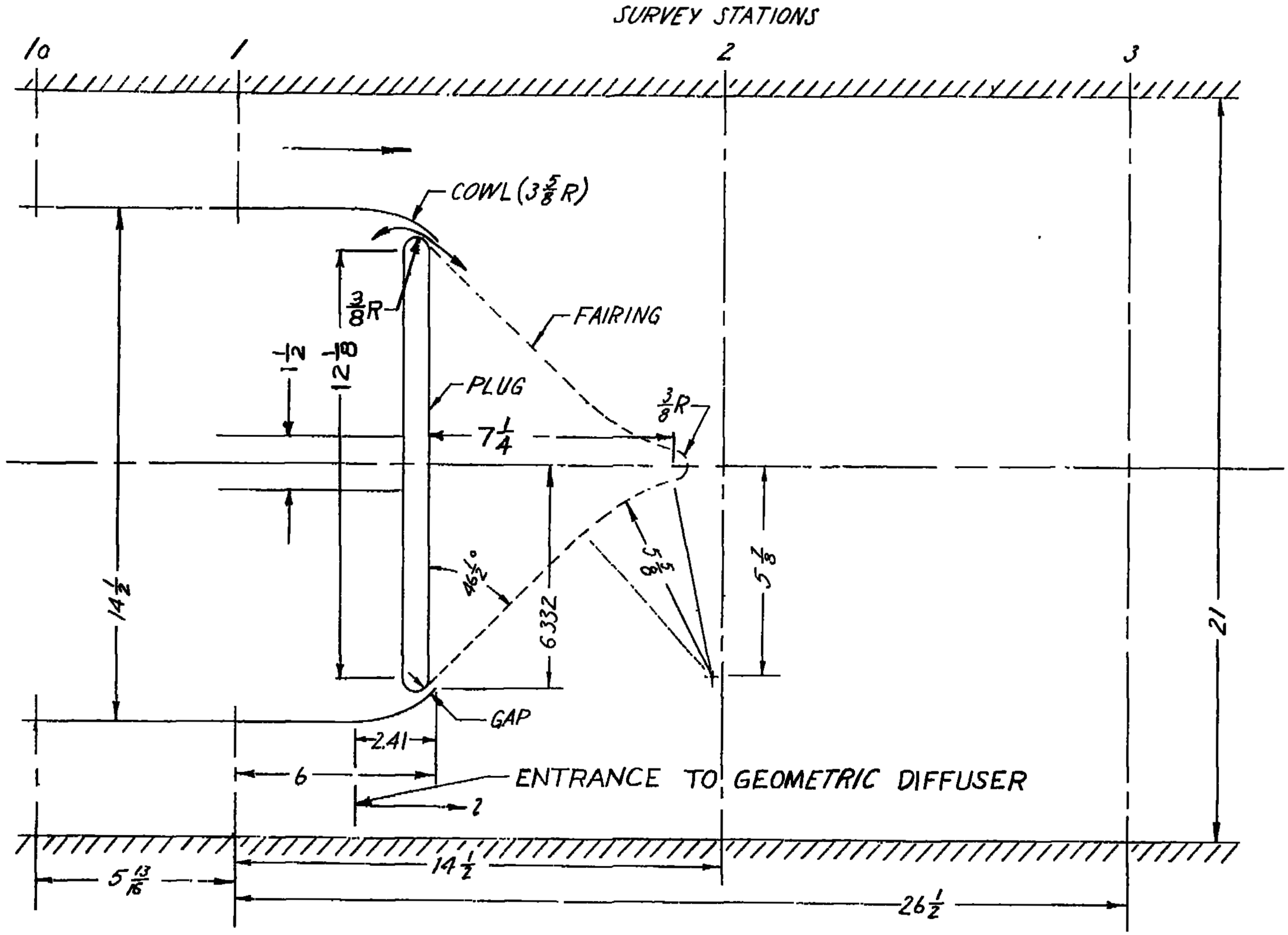


(a) Diagram of apparatus.

Figure 1.- General arrangement of diffuser setup. All dimensions are in inches.



(b) Diffusing region.

Figure 1.- Concluded.

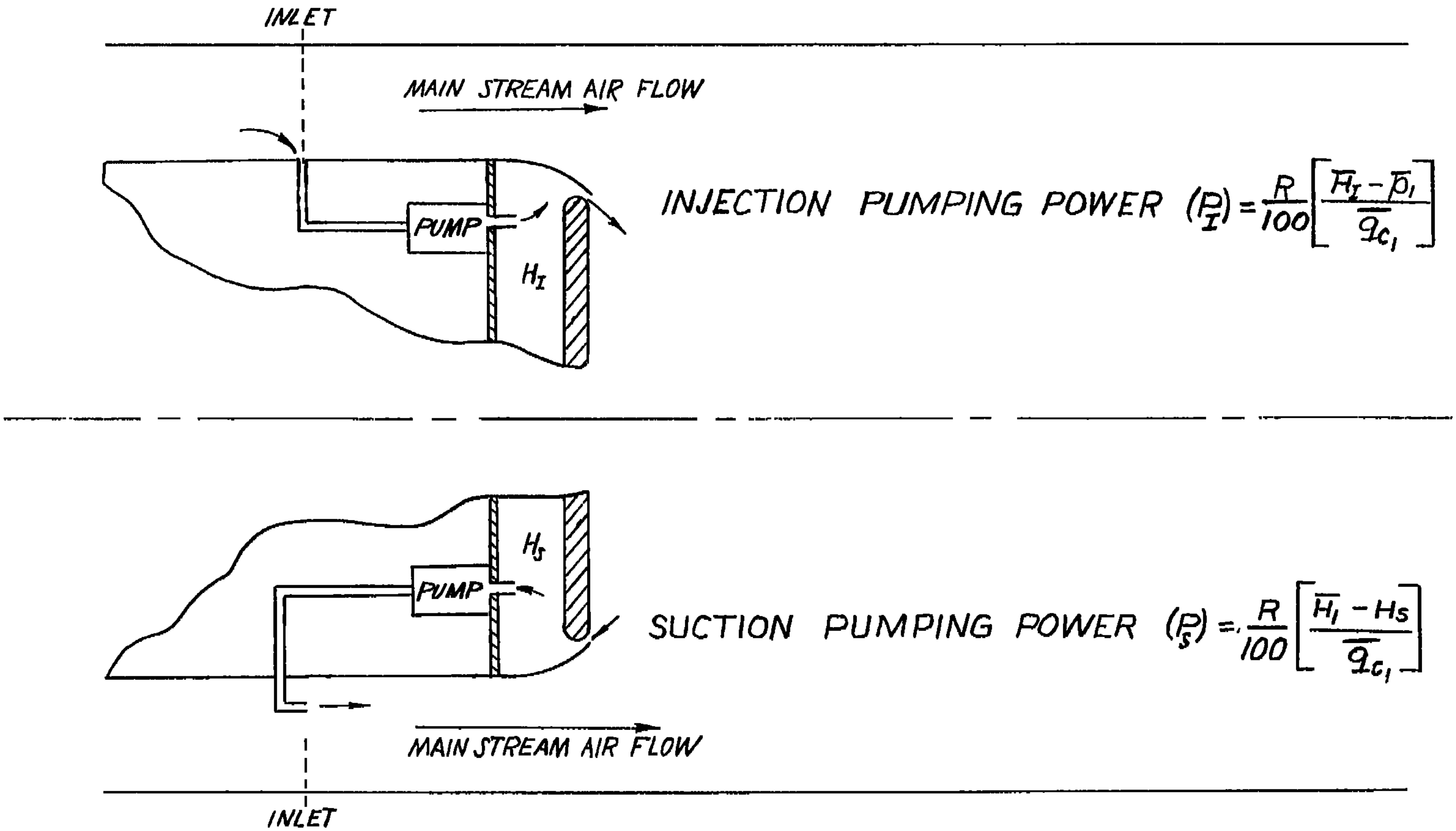


Figure 2.- Hypothetical auxiliary air system.

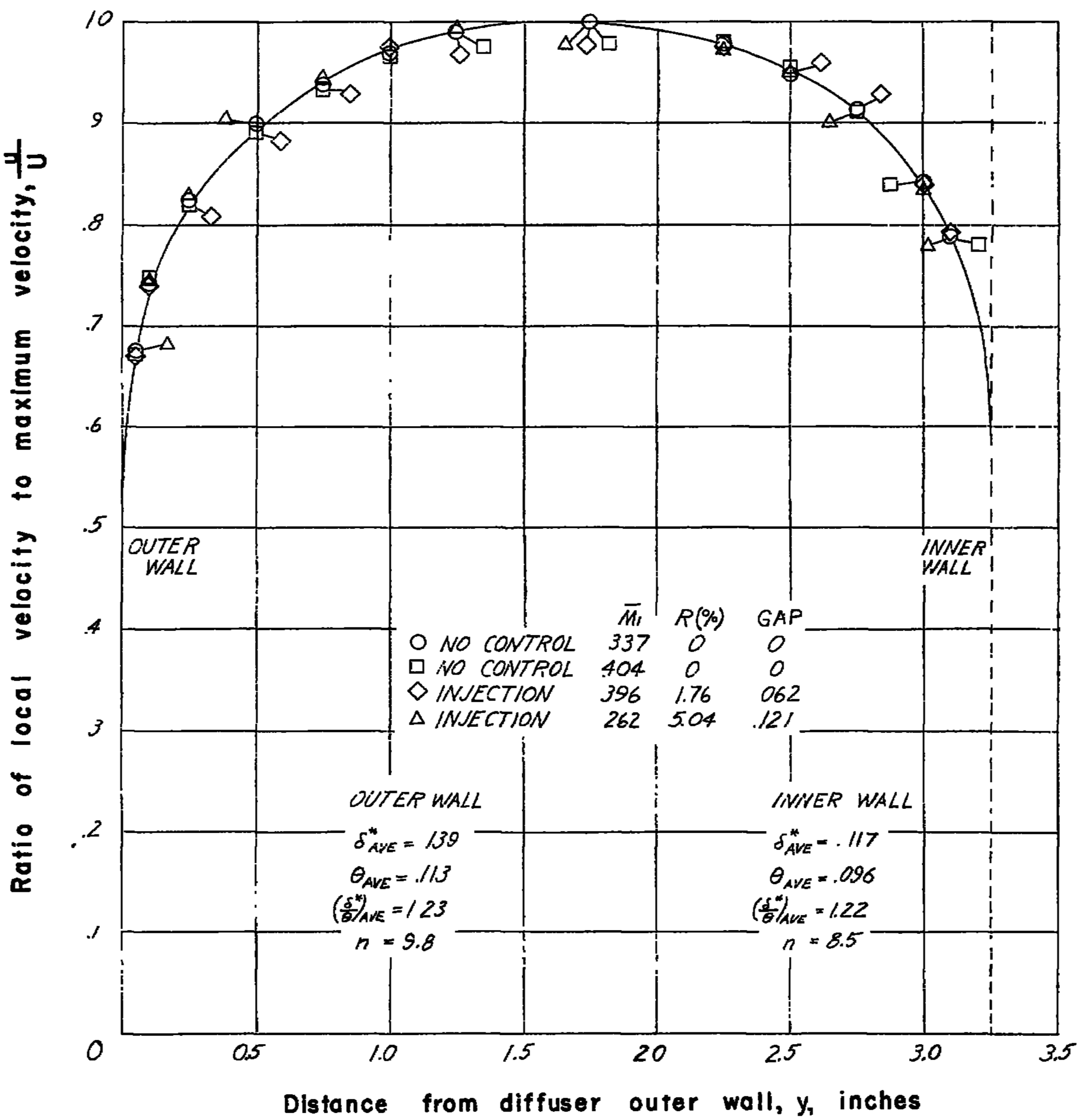


Figure 3.- Inlet velocity profiles at varying Mach number with and without auxiliary flow control.

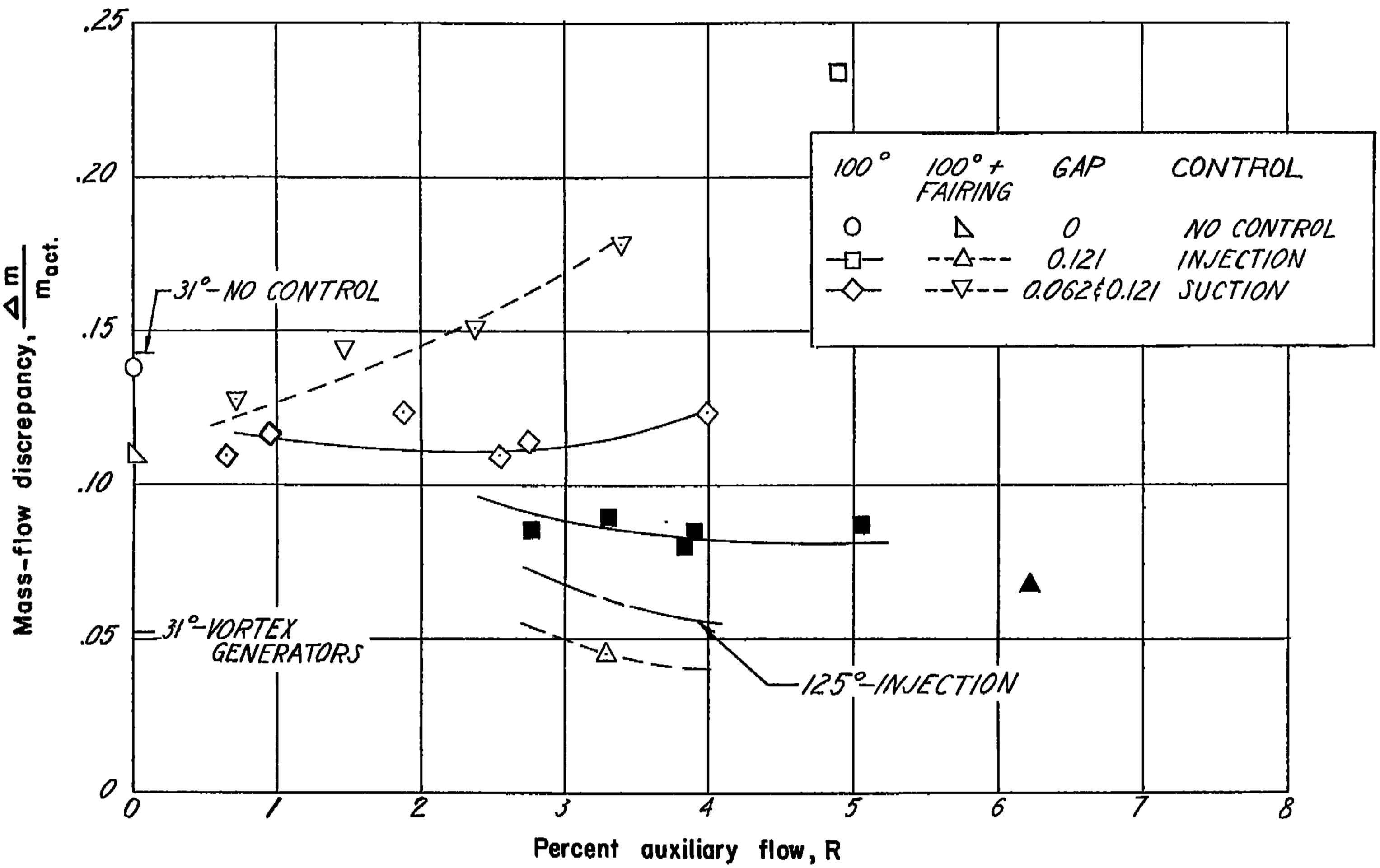


Figure 4.- Variation of the mass-flow discrepancy with percent auxiliary flow at station 3 for $\overline{M_1} \approx 0.26$. Shaded symbols indicate attached flow.

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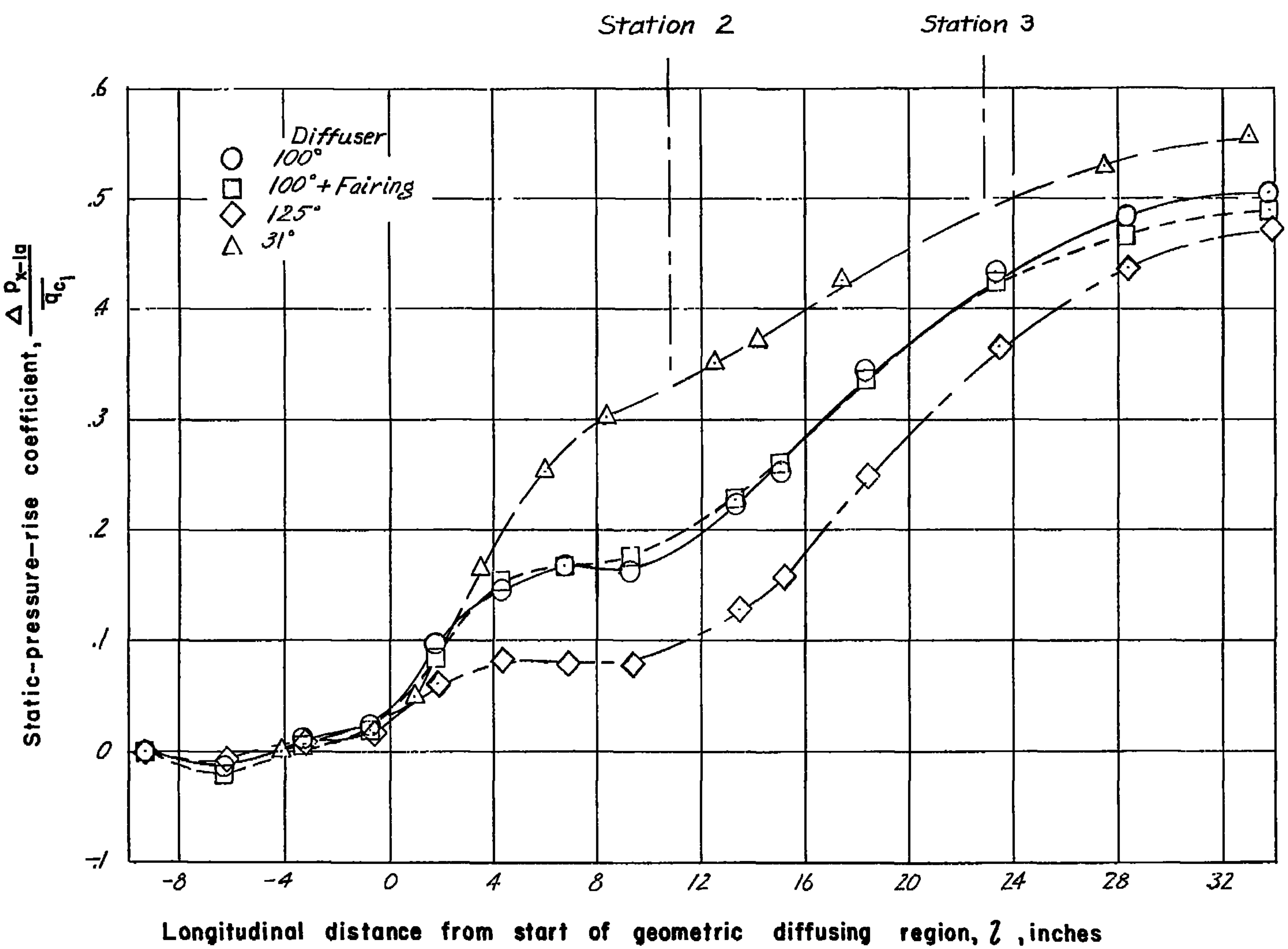


Figure 5.- No-control comparison of static-pressure-rise coefficient along diffuser outer wall.

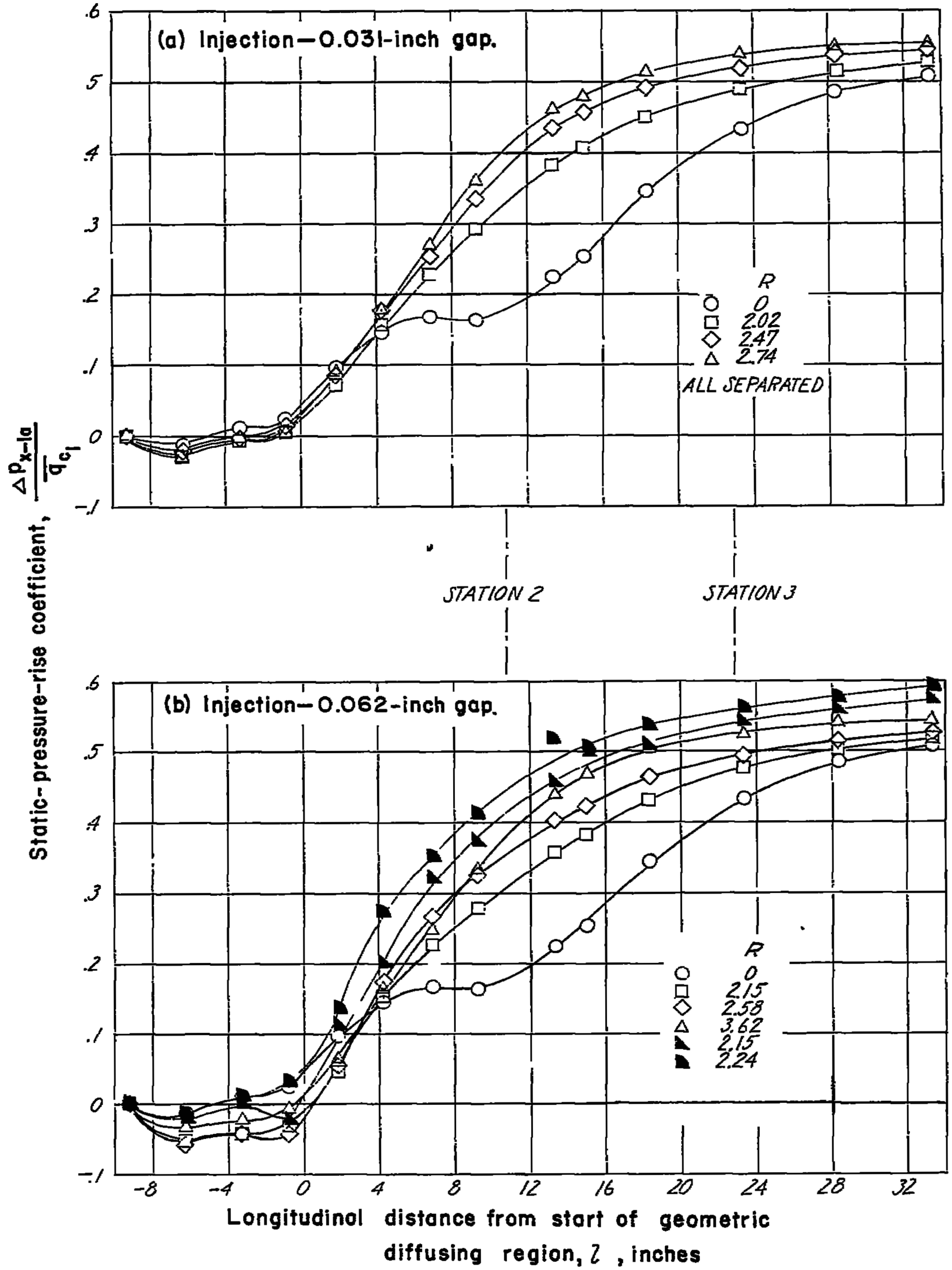


Figure 6.- Static-pressure-rise coefficient along diffuser outer wall for the 100° diffuser. Shaded symbols indicate attached flow.

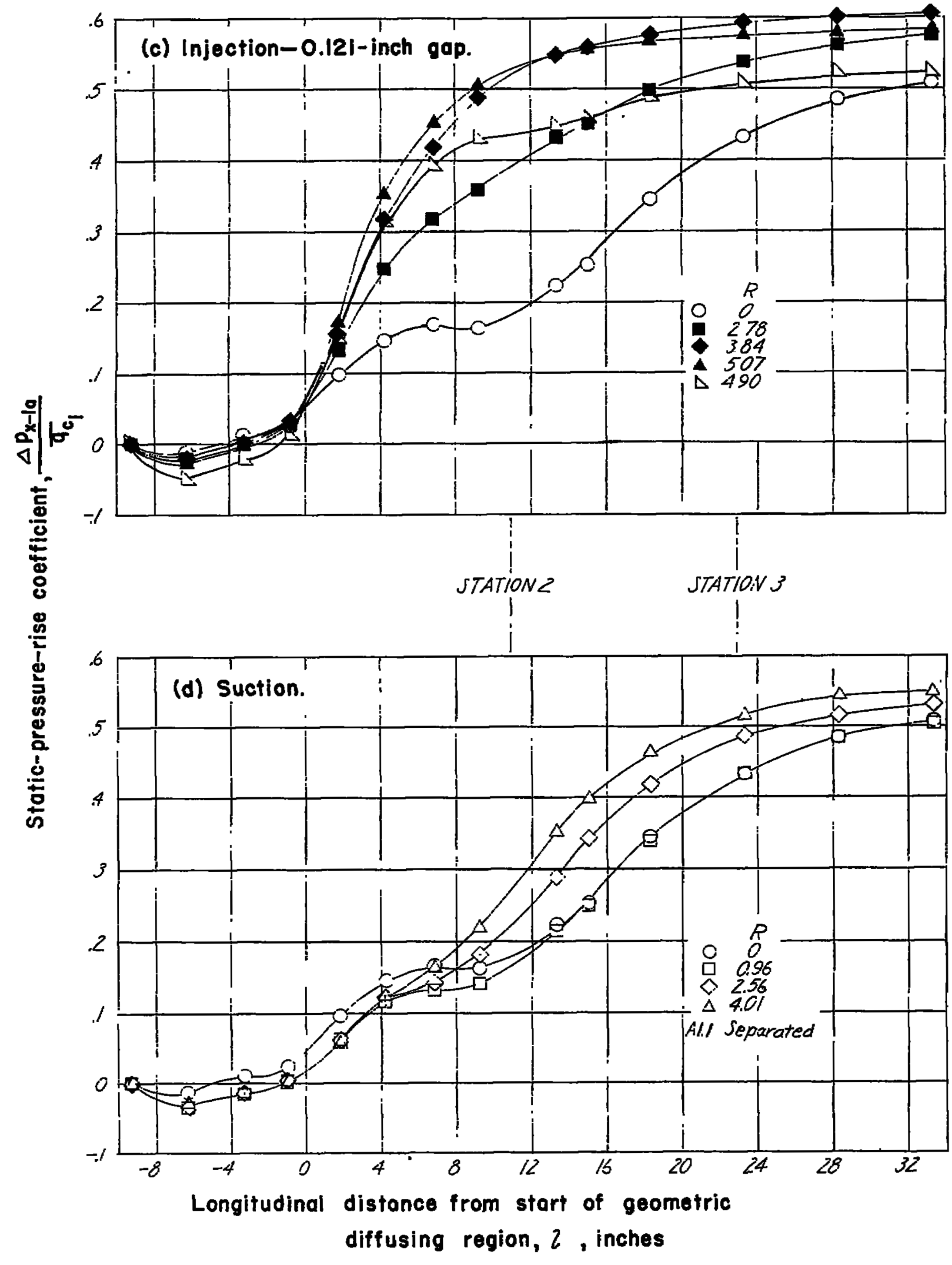


Figure 6.- Concluded.

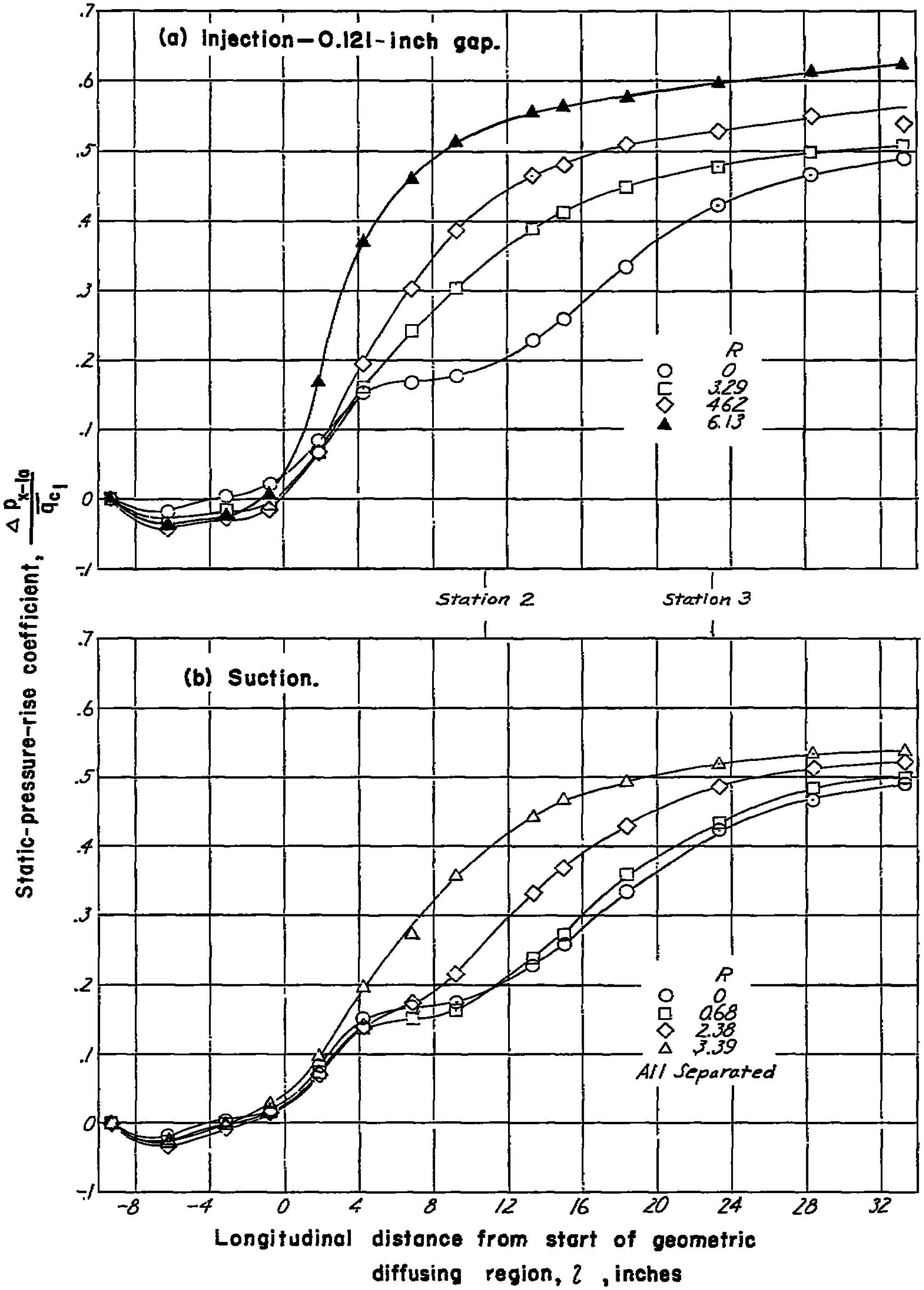


Figure 7.- Static-pressure-rise coefficient along diffuser outer wall for the 100° diffuser and fairing. Shaded symbols indicate attached flow.

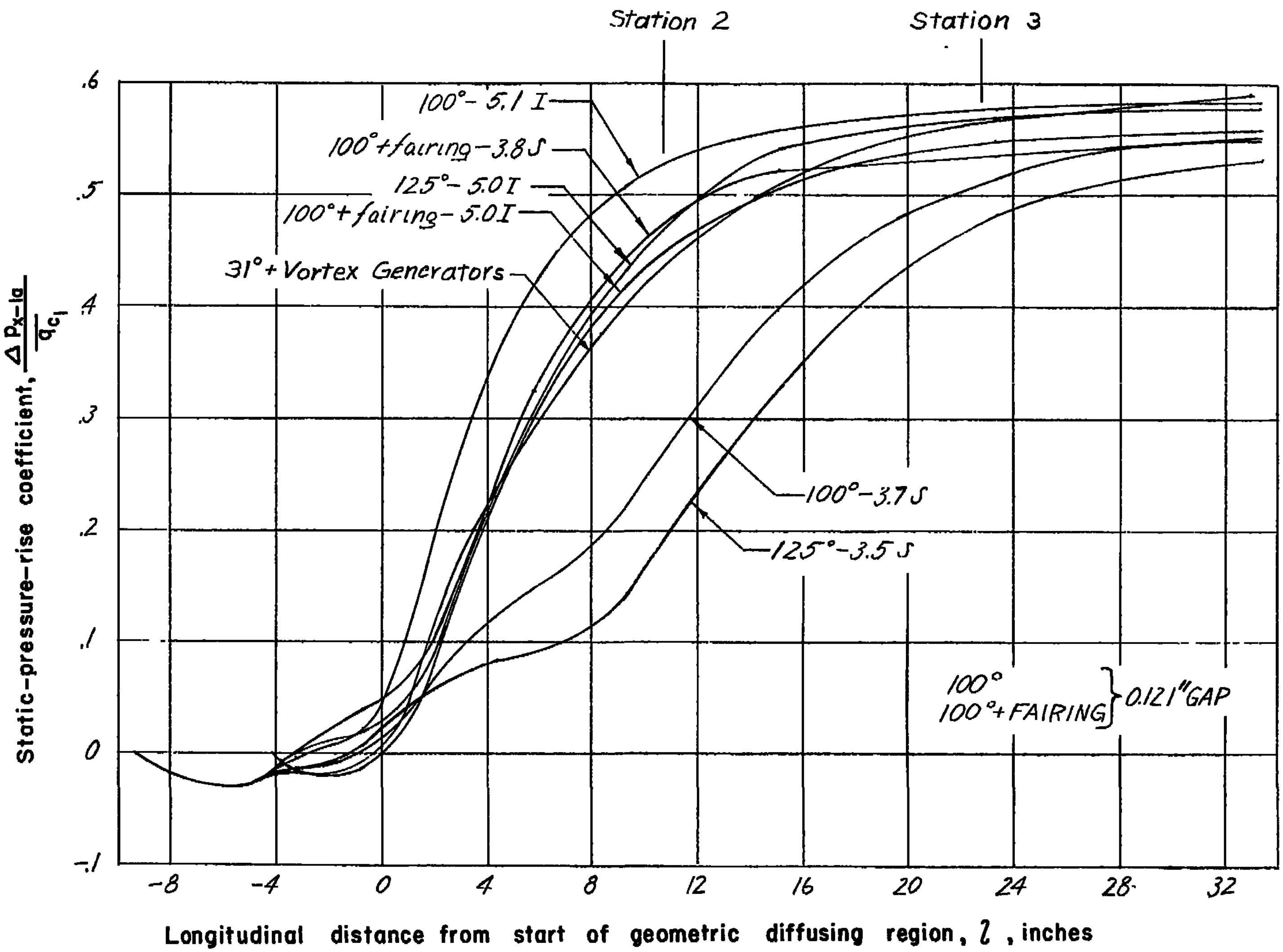


Figure 8.- Control comparison of static-pressure-rise coefficient along diffuser outer wall.

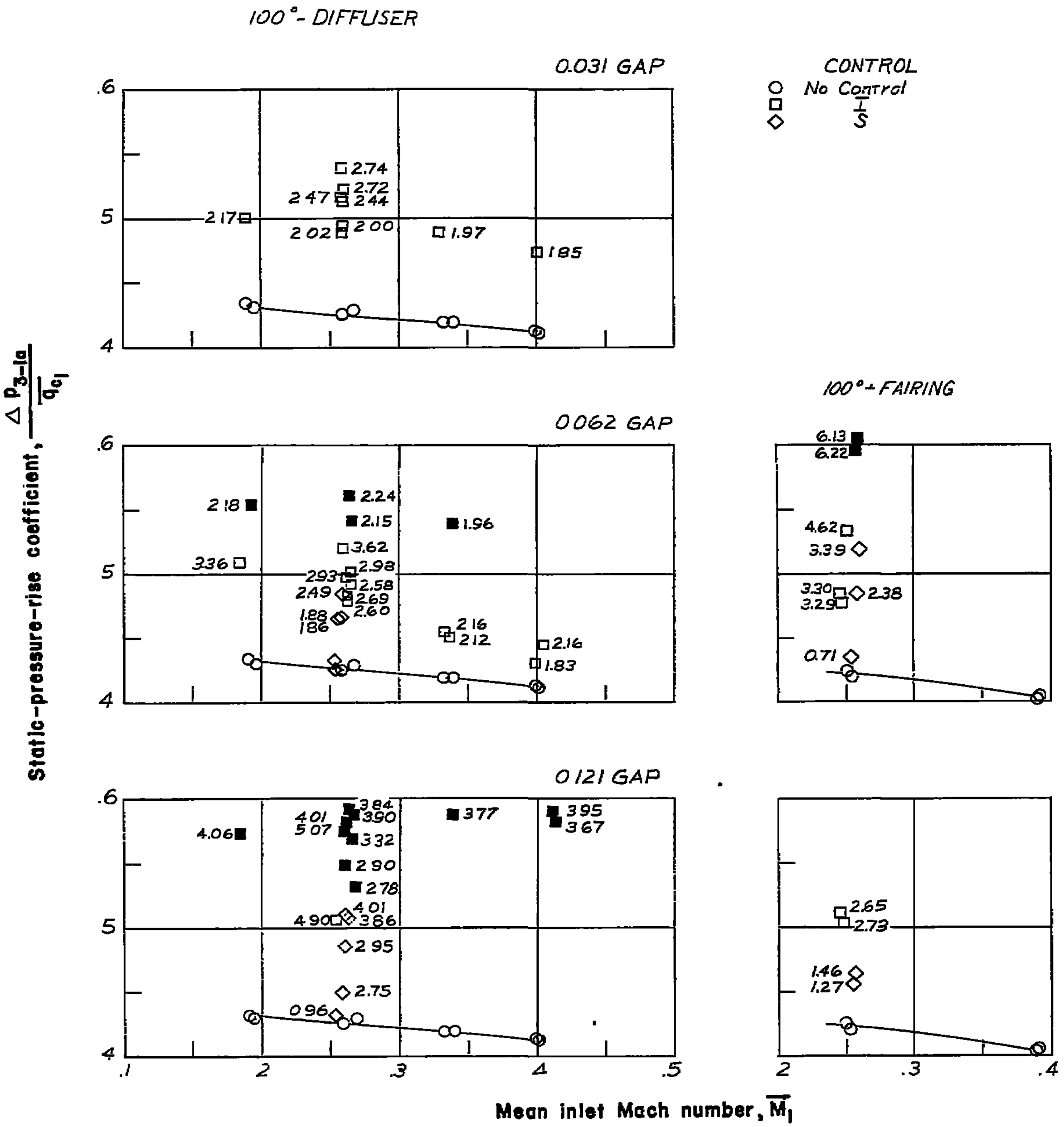


Figure 9.- Variation of static-pressure-rise coefficient at station 3 with mean inlet Mach number. Shaded symbols indicate attached flow. Numbers beside symbols are auxiliary flow rates.

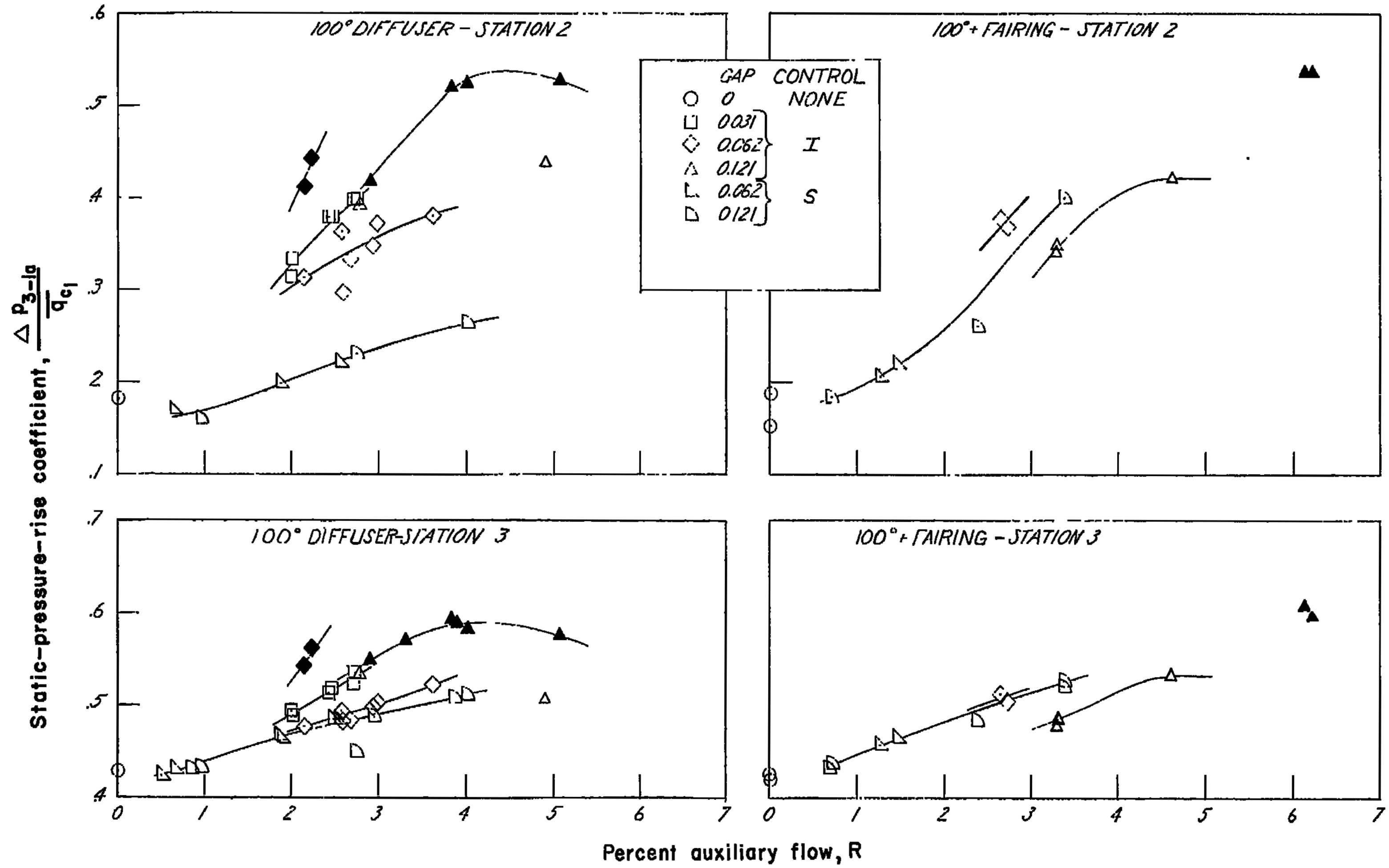


Figure 10.- Variation of static-pressure-rise coefficient with percent auxiliary flow at $\overline{M_1} \approx 0.26$. Shaded symbols indicate attached flow.

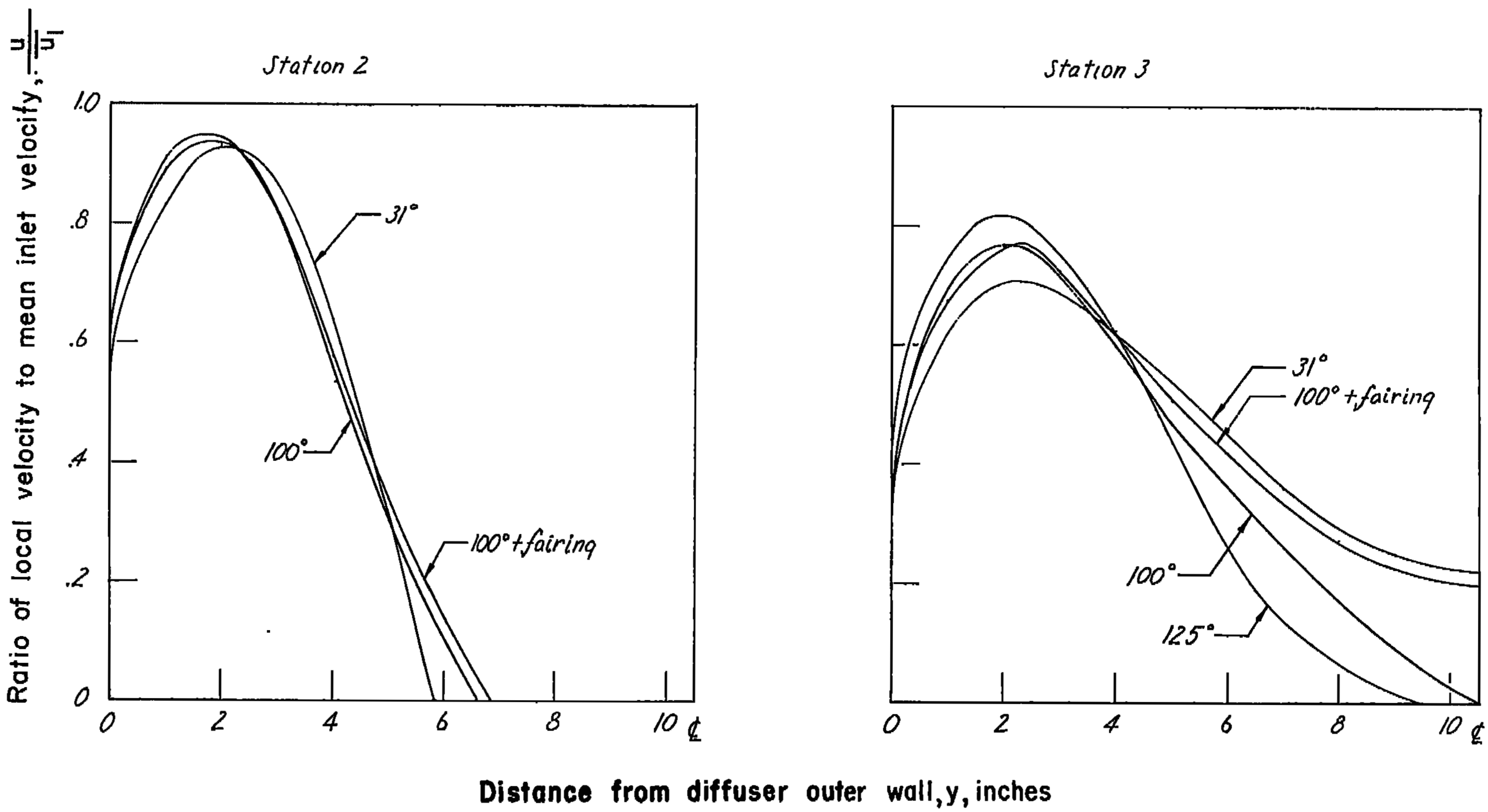
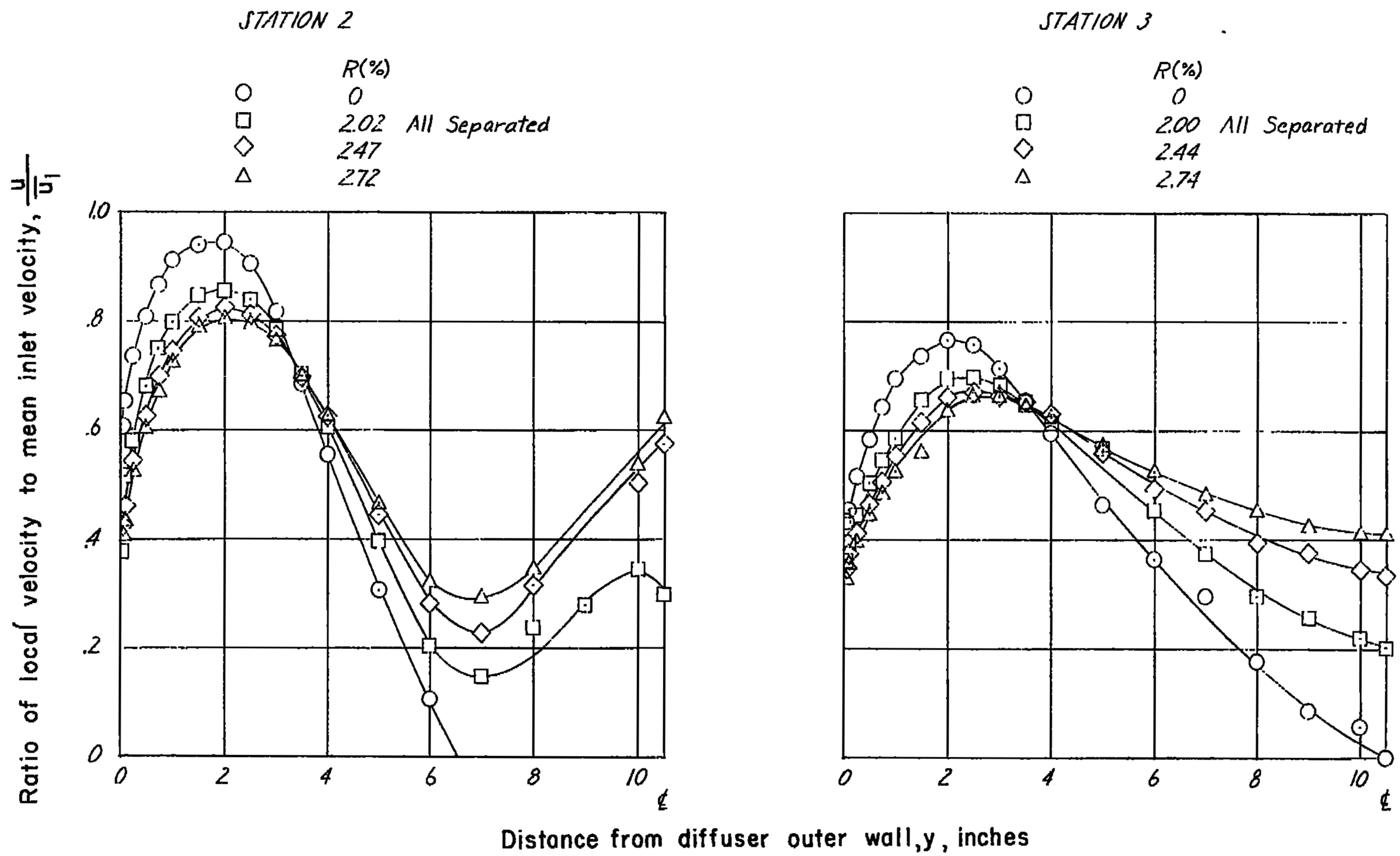
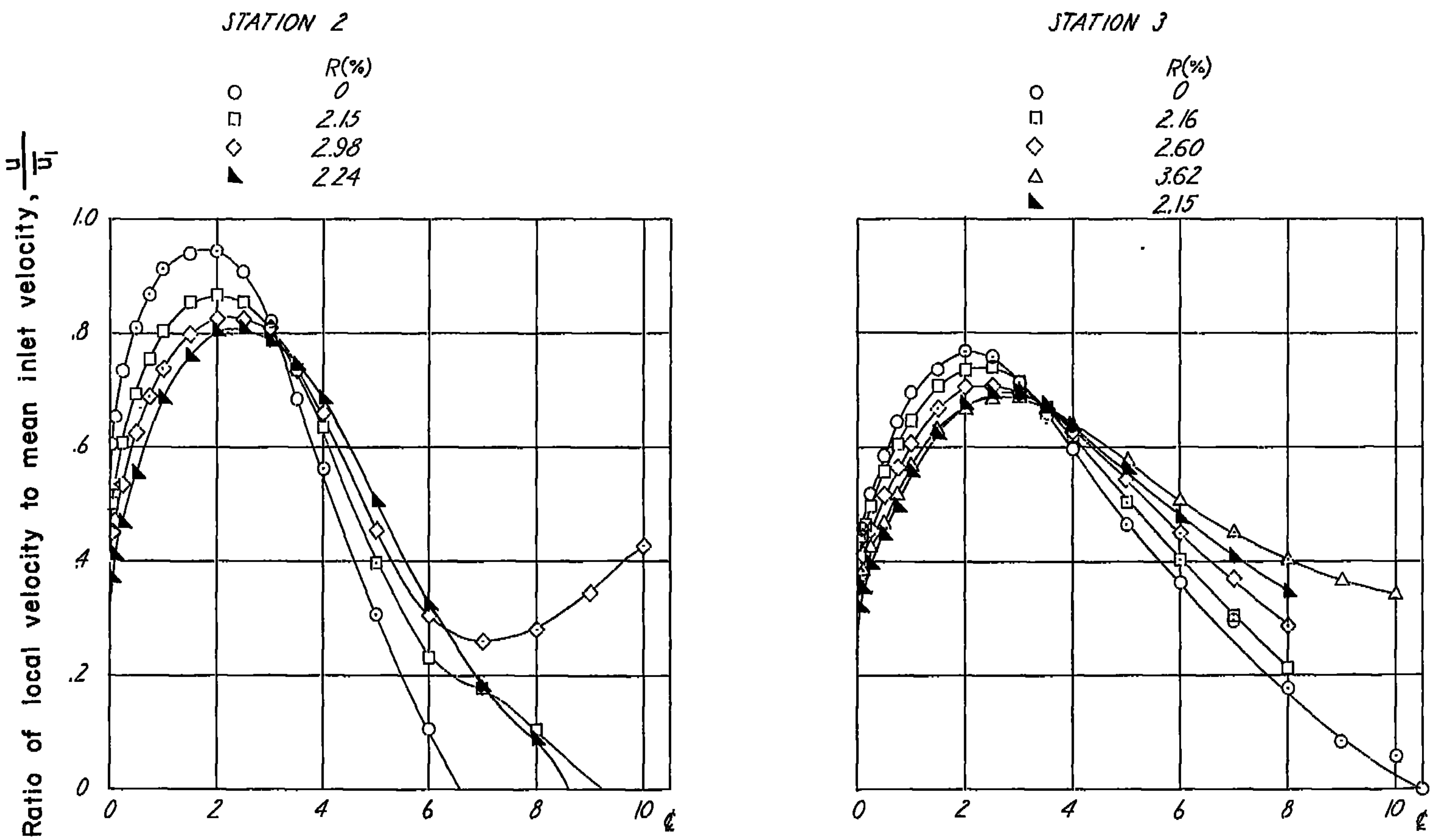


Figure 11.- No-control comparison of velocity profiles at stations 2 and 3.



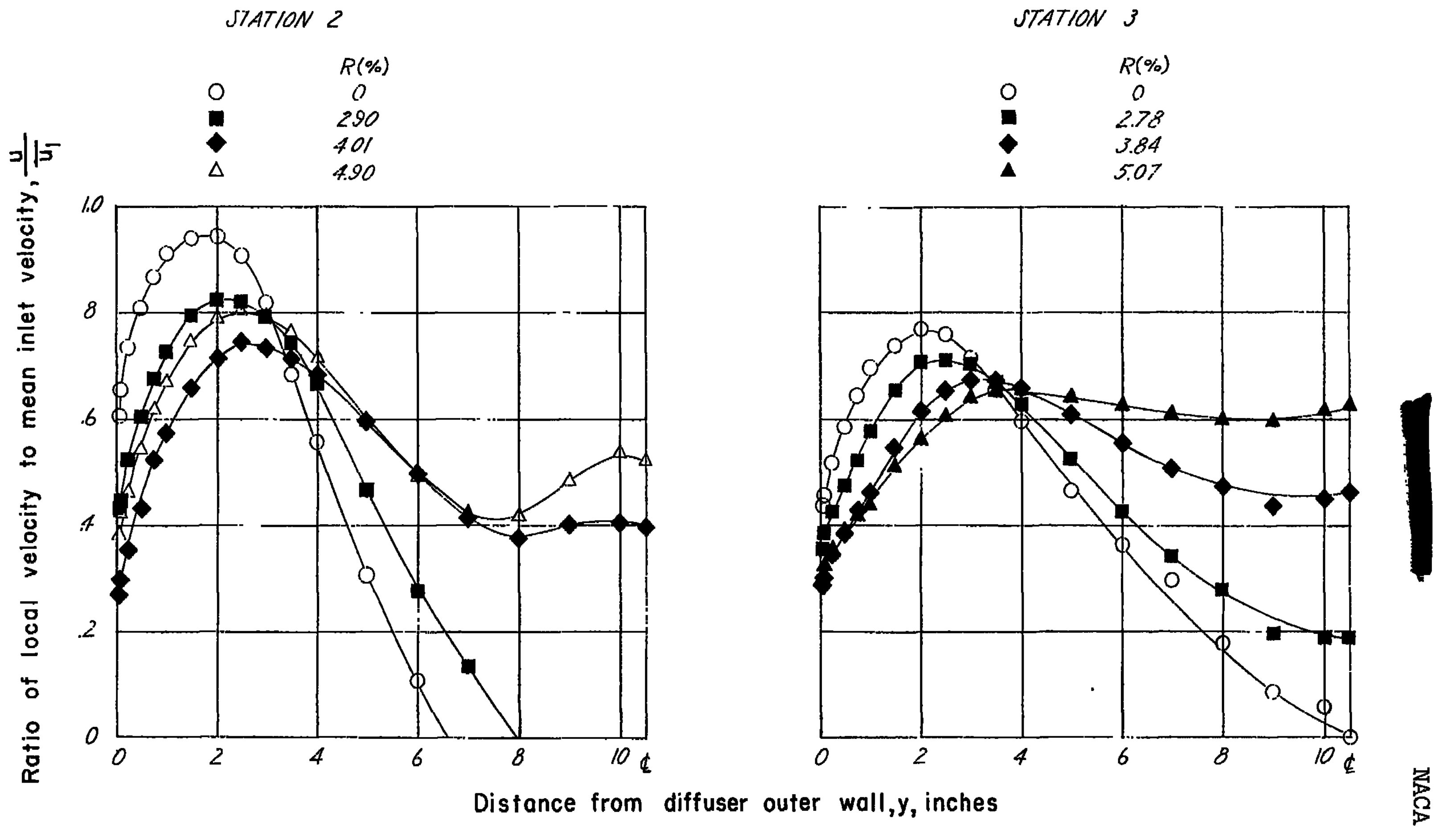
(a) Injection - 0.031-inch gap.

Figure 12.- Exit velocity profiles at stations 2 and 3 for the 100° diffuser. Shaded symbols indicate attached flow.



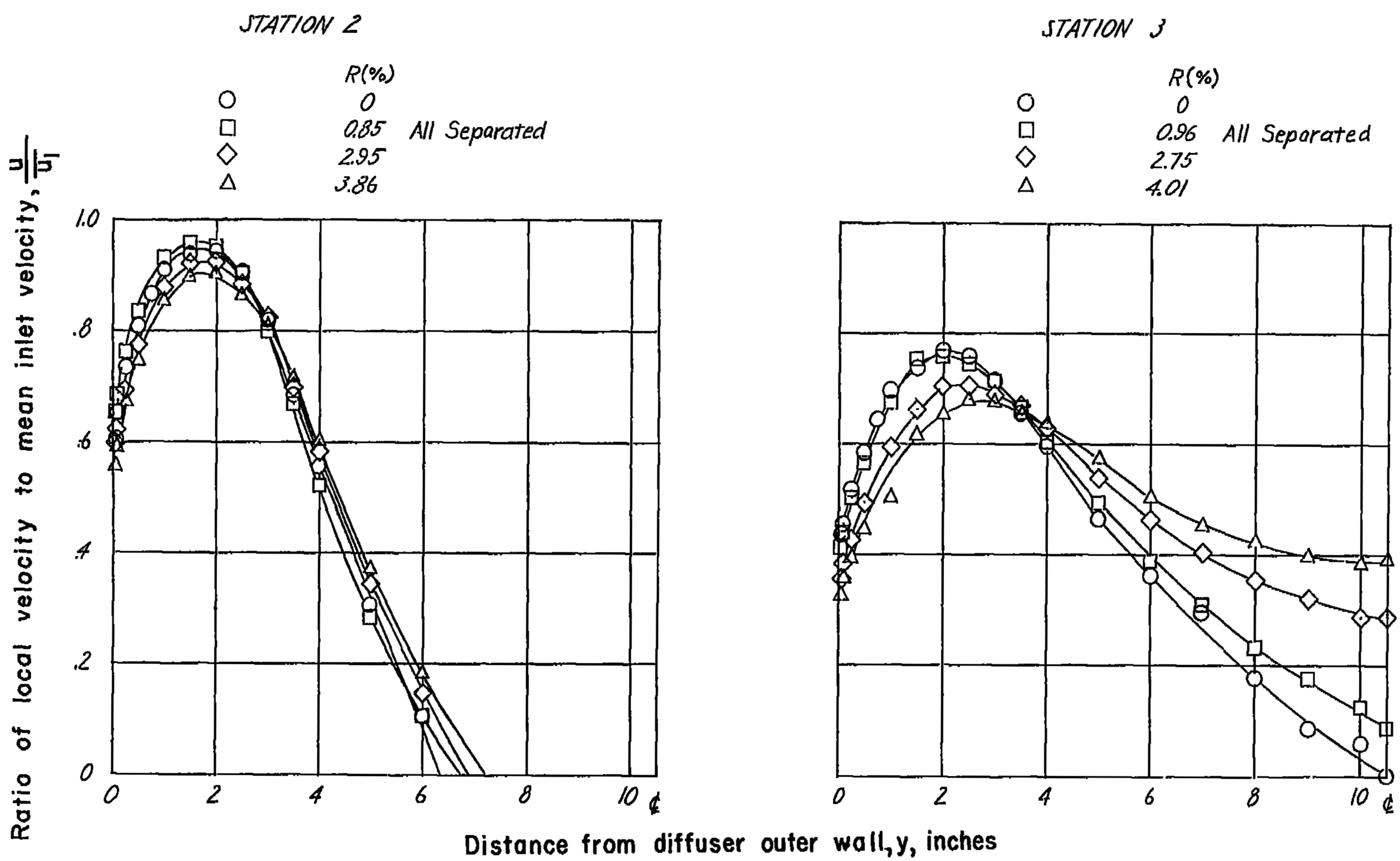
(b) Injection - 0.062-inch gap.

Figure 12.- Continued.



(c) Injection - 0.121-inch gap.

Figure 12.- Continued.



(d) Suction - 0.062- and 0.121-inch gaps.

Figure 12.- Concluded.

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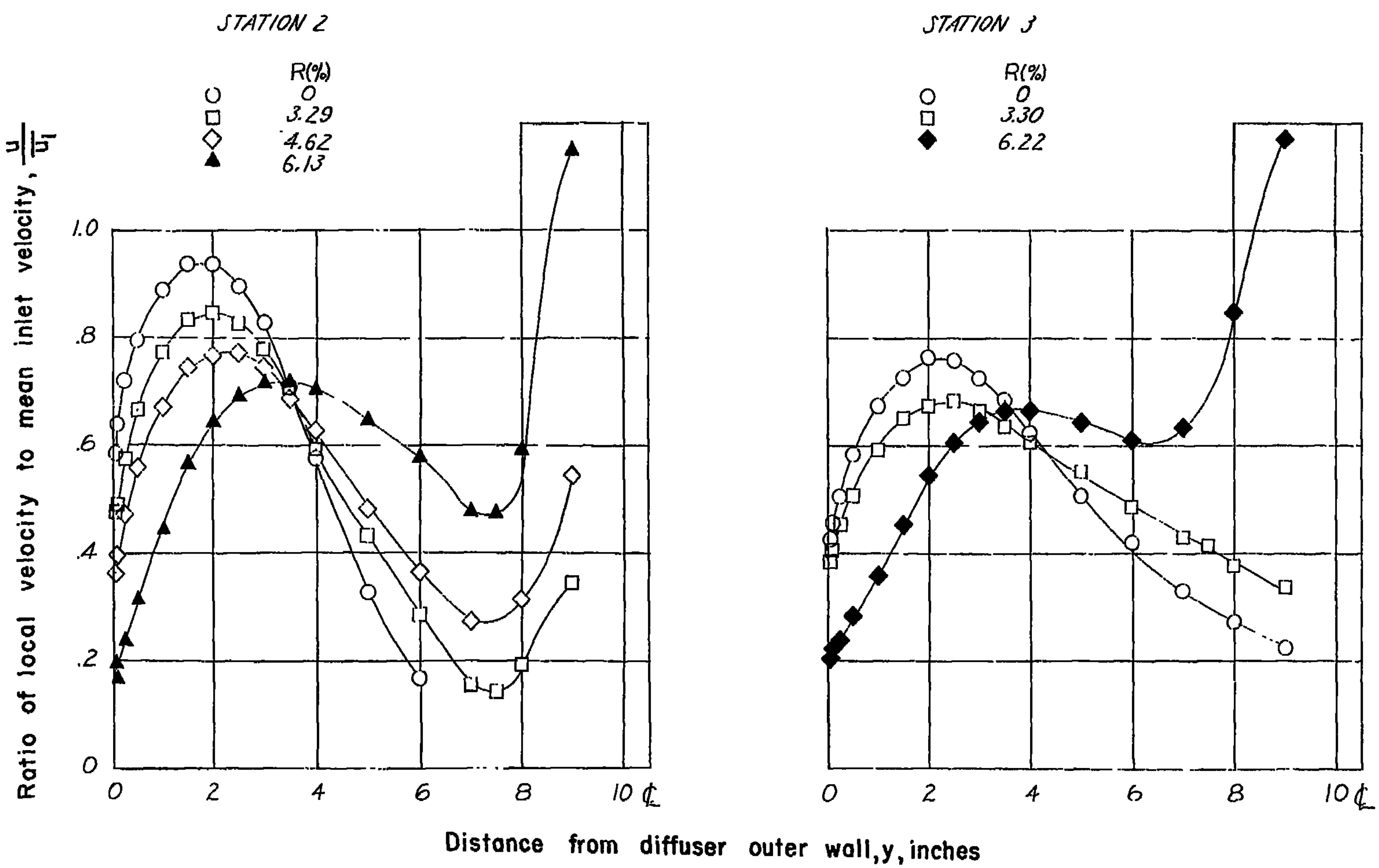

(a) Injection - 0.121-inch gap.

Figure 13.- Exit velocity profiles at stations 2 and 3 for the 100° diffuser and fairing. Shaded symbols indicate attached flow.

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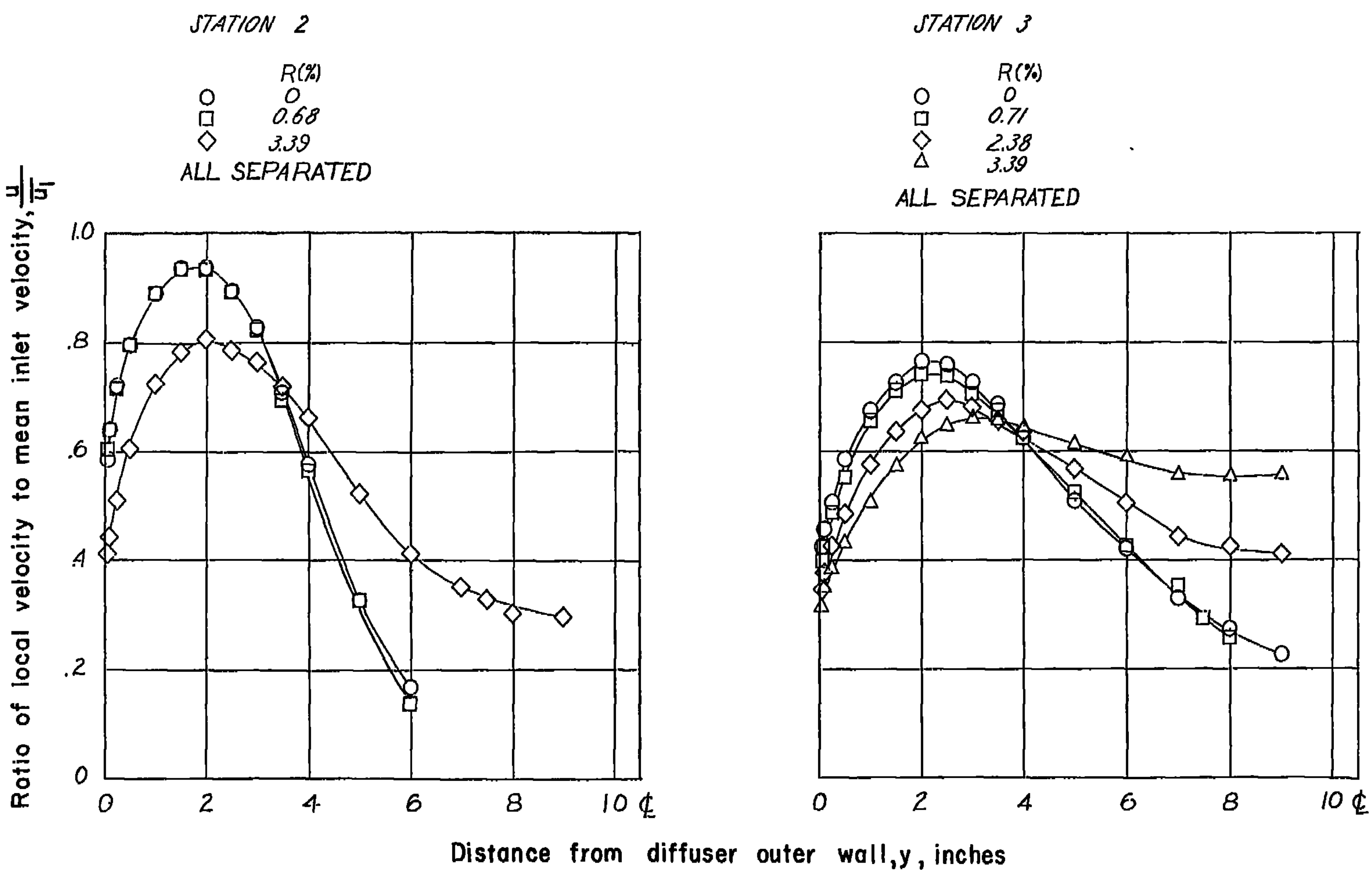

(b) Suction - 0.062- and 0.121-inch gaps.

Figure 13.- Concluded.

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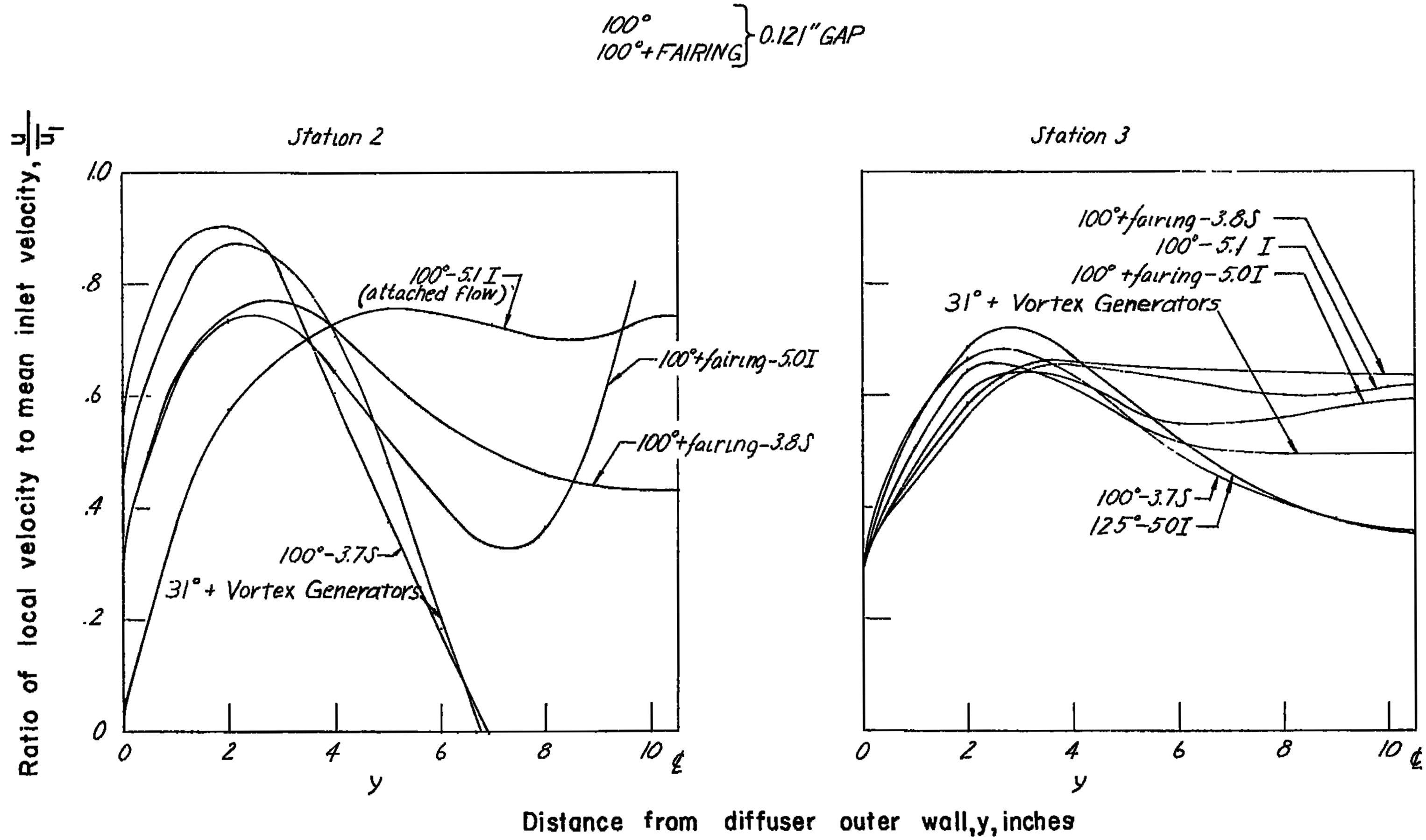

Figure 14.- Comparison of exit velocity profiles at stations 2 and 3 with boundary-layer control.

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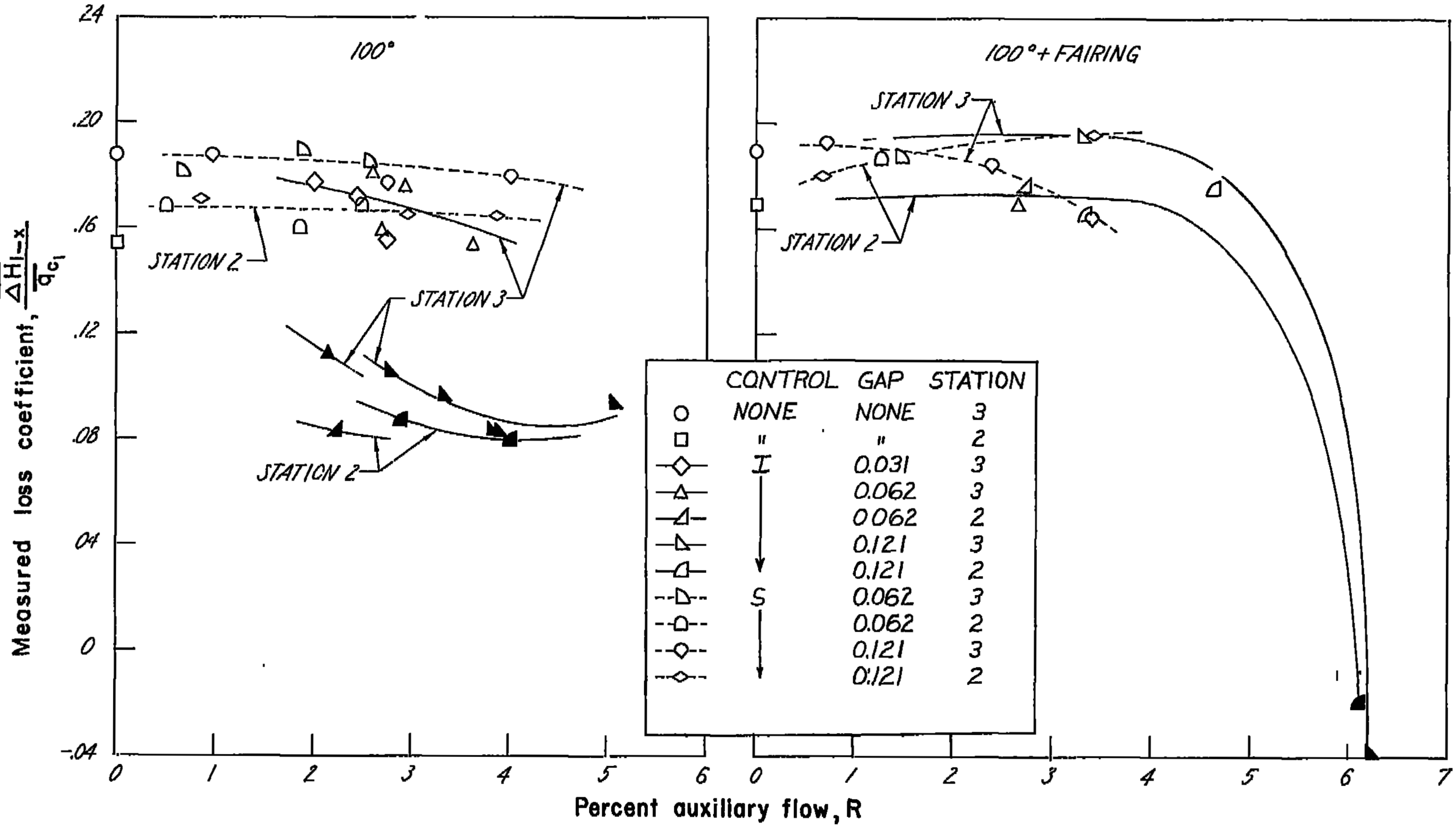

Figure 15.- Variation of measured loss coefficient with percent auxiliary flow at $\overline{M_l} \approx 0.26$. Shaded symbols indicate attached flow.

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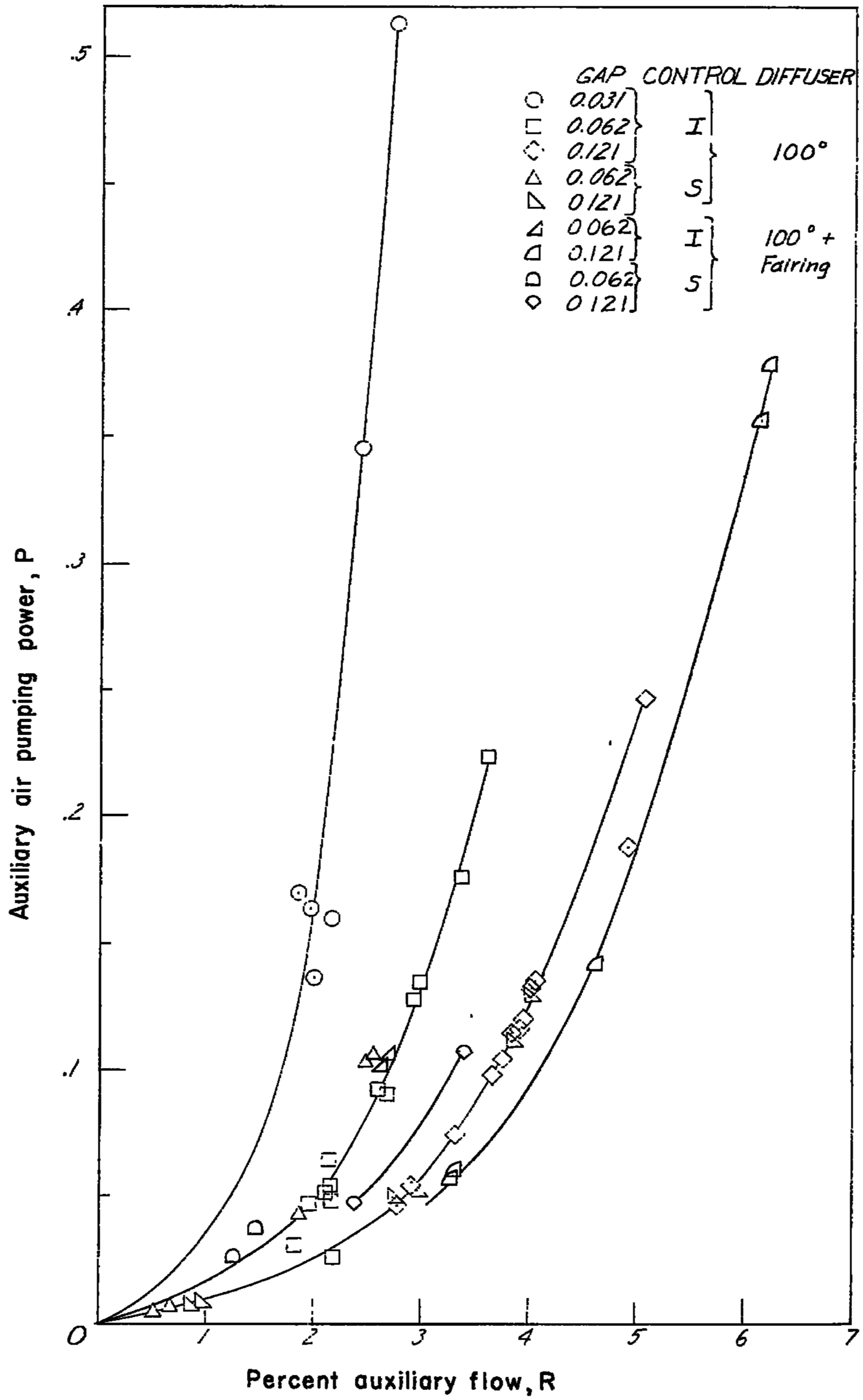

Figure 16.- Variation of auxiliary air pumping power with percent auxiliary flow.

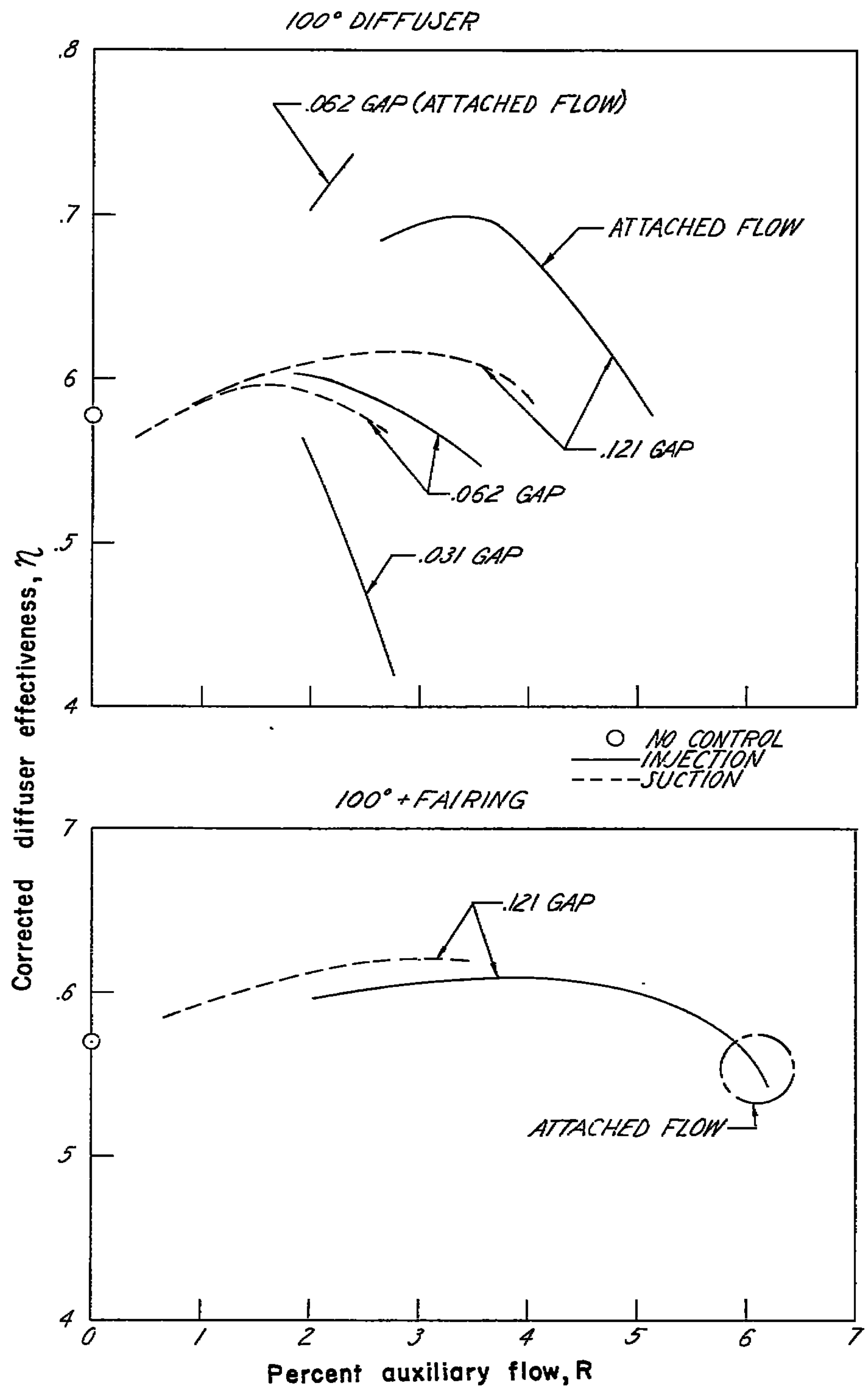

Figure 17.- Variation of corrected diffuser effectiveness at station 3 with percent auxiliary flow.

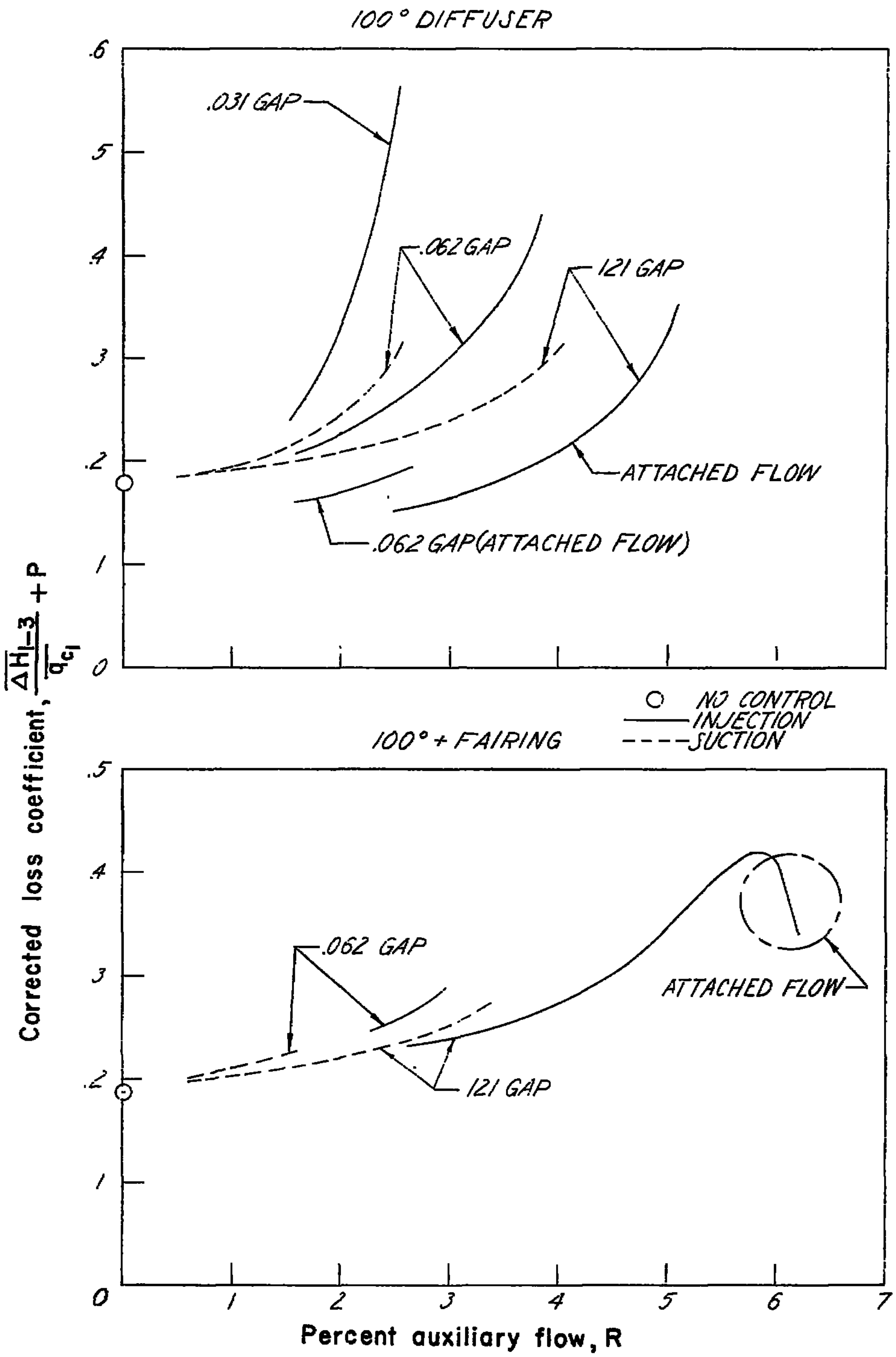

Figure 18.- Variation of corrected loss coefficient at station 3 with percent auxiliary flow.

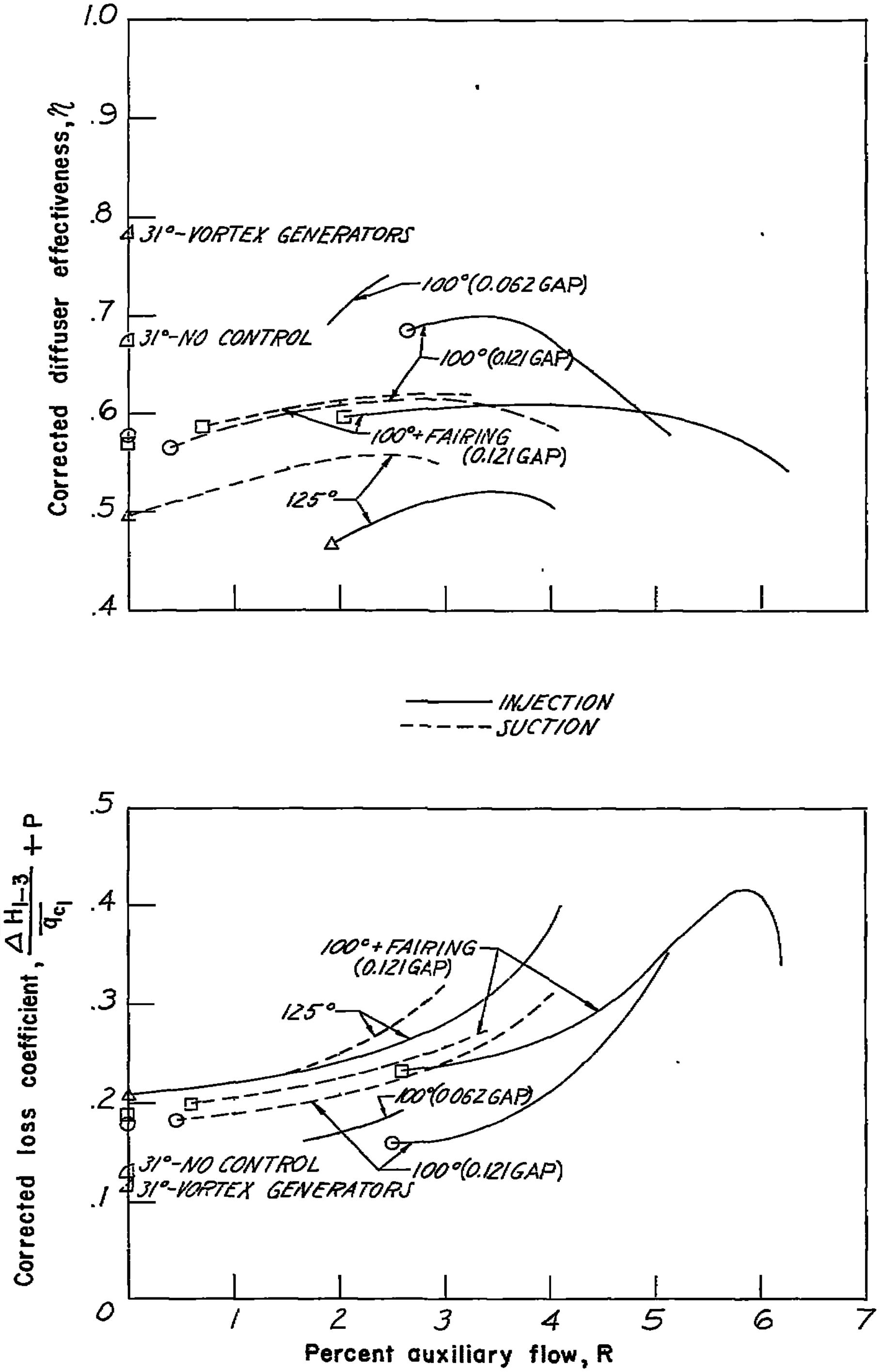

Figure 19.- Comparison of corrected diffuser effectiveness and corrected loss coefficient at station 3 for several diffuser configurations utilizing flow control.

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